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Efficient Oxidative Cleavage of Olefins to Carboxylic Acids with Hydrogen Peroxide Catalyzed by Methyltrioctylammonium Tetrakis(oxodiperoxotungsto)phosphate(3−) under Two-Phase Conditions. Synthetic Aspects and Investigation of the Reaction Course

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The oxidative cleavage of alkenes to carboxylic acids with 40% w/v aqueous hydrogen peroxide catalyzed by methyltrioctylammonium tetrakis(oxodiperoxotungsto)phosphate(3−) (**Ia**) is reported to occur in high yields and selectivities under two-phase conditions in the absence of organic solvents. On the basis of a study of the reaction, two main reaction pathways leading to acids have been recognized, the first one involving the perhydrolysis and the second one the hydrolysis of the epoxide initially formed. The "perhydrolytic" reaction pathway appears to play a primary role in the oxidation of medium- and long-chain alkenes to acids, while it intervenes to a rather limited extent in the oxidation of arylalkenes and C_5-C_7 cycloalkenes. The occurrence of this pathway has been proved by the isolation of the intermediate β-hydroperoxy alcohols and their transformation into acids with H_2O_2 and **Ia**. The course of this transformation, involving an initial oxidation (to α-oxo hydroperoxide) or decomposition (to carbonyl compounds) of the β-hydroperoxy alcohol intermediate, is described. The primary oxidation products, α-hydroperoxy ketones, have been isolated in the case of internal β-hydroperoxy alcohols, whereas their presence has been evidenced with terminal β-hydroperoxy alcohols bearing a secondary hydroxy group. Hydrogen peroxide concentration appears to exert a remarkable influence on medium acidity, and its effects on the reaction efficiency are shown.

Introduction

The oxidative cleavage of alkenes to produce carboxylic acids is a transformation widely used for preparative purposes.[1a] It is commonly achieved by ozonolysis with oxidative workup[2] or by using oxometal reagents such as permanganate[3] or ruthenium tetroxide,[4] the latter preferably employed in catalytic amounts in combination with a number of oxygen donors (NaOCl,[5a−c] $NaIO_4$,[5d,e] or peracetic acid[5f,g]) as primary oxidants.

The early-transition-metal/hydrogen peroxide systems have attracted much interest in recent years in context with the oxidation of organic substrates.[1b] However, there are few reports concerning the olefinic double bond cleavage reaction using these oxidizing systems. They mainly refer to the conversion of (cyclo)alkenes to (di)aldehydes in a nonaqueous medium.[6] To our knowledge, in the past decade only two papers described the use of aqueous hydrogen peroxide in the presence of tris(cetylpyridinium) 12-tungstophosphate[7] or tungstic acid[8] catalysts under homogeneous conditions (*t*-BuOH as the solvent) for the production of carboxylic acids from alkenes. These procedures, however, are of limited practical value, as they require very long reaction times (24 h at 80 °C) and afford moderate-to-low yields of acids with α-olefins.

Our earlier studies[9,10] on the tungstate−phosphate (arsenate)−hydrogen peroxide system under acidic conditions led us to isolate a new class of peroxotungsten complexes with remarkable oxidizing properties, which were identified as quaternary ammonium (phosphonium) tetrakis(oxodiperoxotungsto)phosphates or -arsenates (3−) (**I**).[11,12] Indeed, when used in conjuction with hydrogen

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[1] Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidation of Organic Compounds*; Academic: New York, 1981; (a) Chapter 9, pp 297−299; (b) Chapter 3, pp 48−56; Chapter 9, pp 286−288; Chapter 12, pp 366−368; Chapter 13, pp 387−393; (c) Chapter 3, pp 51−52.

[2] (a) Augustine, R. L., Ed. *Oxidation*; Dekker: New York, 1969; Vol. 1, p 259. (b) Bayley, P. S. *Ozonation in Organic Chemistry*; Academic Press: New York, 1978; Vol. 1.

[3] (a) Starks, C. M. *J. Am. Chem. Soc.* **1971**, *93*, 195. (b) Sam, D. J.; Simmons, H. E. *J. Am. Chem. Soc.* **1972**, *94*, 4024. (c) Krapcho, A. P.; Larson, J. R.; Eldridge, J. M. *J. Org. Chem.* **1977**, *42*, 3749. (d) Lee, D. G.; Chang, V. S. *J. Org. Chem.* **1978**, *43*, 1532.

[4] Lee, D. G.; van der Engh, M. In *Oxidation in Organic Chemistry*; Trahanovsky, W. S., Ed.; Academic Press: New York, 1973; Part B, p 186.

[5] (a) Kleybs, K. A.; Dubeck, M. U.S. Patent 3,409,649, 1968 to Ethyl Corp.; *Chem. Abstr.* **1969**, *70*, 114575. (b) Wolfe, S.; Hasan, S. K.; Campbell, J. R. *J. Chem. Soc., Chem. Commun.* **1970**, 1420. (c) Foglia, T. A.; Barr, P. A.; Malloy, A. J.; Costanzo, M. J. *J. Am. Oil Chem. Soc.* **1977**, *54*, 870A. (d) Starks, C. M.; Washecheck, P. H. U.S. Patent 3,547,962, 1970 to Continental Oil Co.; *Chem. Abstr.* **1971**, *74*, 140895. (e) Carlsen, H. J.; Katsuki, T.; Martin, V. S.; Sharpless, K. B. *J. Org. Chem.* **1981**, *46*, 3936. (f) Washecheck, P. H. Ger. Offen. 2,046,034, 1971 to Continental Oil Co.; *Chem. Abstr.* **1971**, *75*, 35158. (g) Merck, W.; Schreyer, G.; Weigert, W. Ger. Offen. 2,106,307, 1972 to Degussa; *Chem. Abstr.* **1972**, *77*, 151485.

[6] (a) Waldemann, H.; Schwerdtel, W.; Swodenk, W. Ger. Offen. 2,201,456, 1973 and 2,252,674, 1974 to Bayer A.-G.; *Chem. Abstr.* **1973**, *79*, 91679 and **1974**, *81*, 25083. (b) Nippon Oil Co. Jpn. Kokai Tokkyo Koho 82 95,921, 1982; *Chem. Abstr.* **1982**, *97*, 162366.

[7] Ishii, Y.; Yamawaki, K.; Ura, T.; Yamada, H.; Yoshida, T.; Ogawa, M. *J. Org. Chem.* **1988**, *53*, 3587.

[8] Oguchi, T.; Ura, T.; Ishii, Y.; Ogawa, M. *Chem. Lett.* **1989**, 857.

[9] (a) Venturello, C.; Alneri, E.; Lana, G. Ger. Offen. 3,027,349, 1981 (It. Appl. 24478/79); *Chem. Abstr.* **1981**, *95*, 42876. (b) Venturello, C.; Alneri, E.; Ricci, M. *J. Org. Chem.* **1983**, *48*, 3831.

[10] (a) Venturello, C.; Ricci, M. Eur. Pat. Appl. 123,495, 1984 (It. Appl. 20605/83); *Chem. Abstr.* **1985**, *102*, 78375. (b) Venturello, C.; Ricci, M. *J. Org. Chem.* **1986**, *51*, 1599.

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$$Q_3\{XO_4[W(O)(O_2)_2]_4\}$$

I

Q^+ = "onium group"; X = P, As

a; $Q^+ = [(n\text{-}C_8H_{17})_3NCH_3]^+$; X = P

peroxide under two-phase conditions, complexes **I**, especially **Ia**, were found to promote numerous important reactions, such as the epoxidation of simple, nonactivated alkenes,[11-13] as well as their direct dihydroxylation (via epoxidation),[14,15] the ketonization of secondary alcohols,[16,17] and the oxidation of primary alcohols and aldehydes to carboxylic acids.[17]

The list of the oxidative processes achieved with the **I**/H_2O_2 system (and patented) also included the fission of olefinic double bonds into carboxylic acids.[18] In this case, however, results were only partially satisfactory from the synthetic point of view. In fact, while good yields of acids could be obtained with substrates such as styrene and cyclohexene, with acyclic olefins the reaction took place with increasing difficulty as the chain length increased beyond eight C atoms, even at a high catalyst-to-substrate molar ratio (ca. 1:30).

Later on, we had the opportunity to reexamine the aforementioned two-phase approach to olefin-to-carboxylic acid oxidation in more detail. To our surprise, we found that, on excluding the solvent (an aromatic or chlorinated aliphatic hydrocarbon) previously employed in our patent work,[18] the reaction gave significantly improved results with medium- and mostly long-chain alkenes, even at a lower catalyst-to-substrate molar ratio. On the basis of this finding, we could develop an efficient, general procedure for the two-phase oxidation of olefins to carboxylic acids with hydrogen peroxide catalyzed by the very active complex **Ia**.

In the present article, we report the full details of the synthetic method and the results of a complete investigation of the reaction course, which also enable us to accommodate the new aspects observed in a general mechanistic scheme.

Results and Discussion

I. Synthesis of Carboxylic Acids from Olefins with Ia/H_2O_2. The oxidation of alkenes to carboxylic acids is carried out in the absence of the solvent by vigorously stirring a biphase mixture made up of the appropriate olefin, catalyst **Ia**, and 40% w/v aqueous hydrogen peroxide at 85 °C for 5−7 h. Catalyst/substrate molar ratios of 1−1.2:100 and, usually, a 10% molar excess of oxidant over the stoichiometric amount required[19] are employed. Pertinent results are summarized in Table 1.

As shown, a number of olefins are selectively cleaved by the present method to give reasonably pure (when isolated) carboxylic acids in good-to-high yields. Thus, the commercially available even-numbered linear chain α-olefins 1-octene, -decene, and -hexadecene were easily converted into the respective odd-numbered alkanoic acids of one less carbon in 80% yields (entries 1, 2, and 6). Likewise, styrene gave an 87% yield of benzoic acid (entry 3). The oxidation of the unsymmetrical internal olefins *trans*-2-octene and *trans*-4-decene (entries 4 and 5) produced hexanoic acid in 81% and 78% yields, together with acetic acid (78%) and butanoic acid (80%), respectively, while the oxidation of *trans*-5-decene gave a 77% yield of pentanoic acid (entry 7). In a similar manner, on oxidation of oleic acid (entry 8), pelargonic (nonanoic) acid and azelaic (nonanedioic) acid were obtained in 82% and 79% yields, respectively.

Cyclopentene, cyclohexene, and 1-methylcyclohexene were cleaved readily under the reaction conditions, with the first two substrates affording an 87% yield of glutaric and adipic acid, respectively (entries 9 and 10), and the third one an 85% yield of 6-oxoheptanoic acid (entry 11). The oxidation of cycloheptene (entry 12) was somewhat less satisfactory, with pimelic (heptanedioic) acid being obtained in 74% yield. In this context, it is of interest that unsaturated medium-sized rings (e.g., eight- and ten-membered) gave poor or insignificant amounts of the expected diacids. Thus, oxidation of *cis*-cyclooctene (entry 13) gave only 24% of suberic (octanedioic) acid, together with minor amounts of other acidic components (for details, see Table 1, footnote *k*). In the case of *cis*-cyclodecene (entry 14), the yield of sebacic (decanedioic) acid dropped to less than 1%, while 5-ketosebacic acid (25%), together with its semialdehyde (6,10-dioxodecanoic acid, 5−6%), was the major acidic product (for other acidic components formed, see Table 1, footnote *m*). With both substrates, several neutral products (mostly not further investigated) were formed along with significant amounts of heavy materials. 1,4-Cyclooctanedione was found to be the major GC component of the neutral fraction in the oxidation of *cis*-cyclooctene.

Diolefins also underwent oxidative cleavage, as illustrated in Table 1 (entry 15) by the oxidation of 1,7-octadiene. In this case, however, the isolated yield of the expected adipic acid was considerably lower (60%) than that obtained from the oxidation of cyclohexene.

It is noteworthy that the overoxidation product resulting from a loss of one carbon was generally formed ($<5\%$) together with the expected acid. In several cases (see Table 1, footnote *c*), the acid of two less carbons was also found.

II. The Course of the Reaction. A study of the reaction was undertaken to probe into the nature of the oxidation pathway which leads to carboxylic acids from olefins. Given the peroxidic character of catalyst **Ia** and its known[11-13] epoxidizing ability, the epoxidation of the alkene had to be regarded as the early stage of the reaction.

In agreement with this view, the aforementioned[7,8] tungsten-promoted oxidations of alkenes to acids with aqueous hydrogen peroxide under homogeneous conditions were proposed to follow a course which, apart from the catalyst and reaction medium used, corresponds to

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(11) Venturello, C.; D'Aloisio, R.; Ricci, M. Eur. Pat. Appl. 109,273, 1984 (It. Appl. 24154A/82); *Chem. Abstr.* **1984**, *101*, 191668.

(12) Venturello, C.; D'Aloisio, R.; Bart, J. C. J.; Ricci, M. *J. Mol. Catal.* **1985**, *32*, 107.

(13) Venturello, C.; D'Aloisio, R. *J. Org. Chem.* **1988**, *53*, 1553.

(14) Venturello, C.; Gambaro, M. Eur. Pat. Appl. 146,374, 1985 (It. Appl. 24203A/83); *Chem. Abstr.* **1985**, *103*, 195855.

(15) Venturello, C.; Gambaro, M. *Synthesis* **1989**, 295.

(16) Venturello, C.; Gambaro, M.; Ricci, M. Eur. Pat. Appl. 232,742, 1987 (It. Appl. 19098A/86); *Chem. Abstr.* **1988**, *108*, 131028.

(17) Venturello, C.; Gambaro, M. *J. Org. Chem.* **1991**, *56*, 5924.

(18) Venturello, C.; Ricci, M. Eur. Pat. Appl. 122,804, 1984 (It. Appl. 20604A/83); *Chem. Abstr.* **1985**, *102*, 95256.

(19) Oxidation of trisubstituted and internal disubstituted olefins to acids obeys a 1:3 and 1:4 substrate-to-hydrogen peroxide stoichiometry, respectively. The molar ratio required becomes 1:5 with monosubstituted terminal olefins as the coproduced formic acid can be further oxidized to carbon dioxide.

Table 1. Oxidative Cleavage of Olefins to Carboxylic Acids with H_2O_2 Catalyzed by Tetrakis(oxodiperoxotungsto)phosphate Ia[a]

entry	olefin (50 mmol)	**Ia** (mmol)	H_2O_2 (mmol)	time (h)	product(s)	yield[b] (%)	purity[c] (%)
1	1-octene	0.5	275	6	heptanoic acid	80	95
2	1-decene	0.6	275	6	nonanoic acid	80	95
3	styrene[d]	0.5	275	5	benzoic acid	87	97[e]
4	*trans*-2-octene	0.5	220	6	hexanoic acid	81	97
					acetic acid	78[f]	
5	*trans*-4-decene	0.5	220	6	hexanoic acid	77[g]	
					butanoic acid	80[g]	
6	1-hexadecene	0.6	275	6	pentadecanoic acid	80	95
7	*trans*-5-decene	0.5	220	6	pentanoic acid	77	96
8	oleic acid	0.6	275	5	nonanoic acid	82[g]	
					nonanedioic acid	79[g]	
9	cyclopentene	0.6	230	7	glutaric acid	87	97
10	cyclohexene[d]	0.6	220	6	adipic acid	87	99[h]
11	1-methylcyclohexene[d]	0.5	175	6	6-oxoheptanoic acid	85	96[i]
12	cycloheptene	0.6	230	7	heptanedioic acid	74	92
13	*cis*-cyclooctene[j]	0.3	137.5	7	octanedioic acid	24[g,k]	
14	*cis*-cyclodecene[j]	0.3	137.5	7	decanedioic acid	<1[g]	
					5-oxodecanedioic acid	25[g,l,m]	
					6,10-dioxodecanoic acid	5−6[g,n]	
15	1,7-octadiene[j]	0.6	250	7	adipic acid	60	99

[a] All reactions were performed without added solvent at 85 °C using 40% w/v aq H_2O_2, in a 10−37.5% molar excess over the stoichiometric amount required.[19] [b] Unless otherwise noted, the yield (based on substrate charged) refers to the isolated product which, where necessary, was purified by either distillation (entries 1, 2, and 6), elution on column (entries 9, 11, and 12), or recrystallization from acetonitrile (entry 15) (for details, see Experimental Section). [c] Determined by GC after silylation with BSTFA (at 60 °C) or methylation with CH_2N_2 (for monocarboxylic acids). Unless otherwise stated, the product was mainly contaminated by the next lower acid. In entries 1, 2, 6, and 12, it also showed 0.4−0.7% contamination by the overoxidation product of two less carbons. [d] Water (5 mL) was introduced into the reactor together with the olefin and catalyst to achieve better control of the initial exothermicity during the hydrogen peroxide addition. [e] Phenylacetic acid was the major byproduct. [f] Yield determined by GC (*n*-PrOH as an internal standard) on the combined aqueous solutions (original aqueous layer, mother liquor from acid extraction, and washing waters; see Experimental Section) after dilution with acetone. [g] Yield determined by GC (internal standard) on the organic layer as such (entries 5 and 8) or the acid fraction (entries 13 and 14) after silylation (for details, see Experimental Section). [h] Refers to the major crop (containing 0.3% of inorganic residue). The minor crop (containing 1% of inorganic residue) was obtained 96% pure (see Experimental Section). [i] In addition to the overoxidation product 5-oxohexanoic acid (0.5%),[89] additional contaminants were glutaric acid (0.4%), adipic acid (0.3%),[90] and δ-acetoxypentanoic acid (1%) (GC−MS (as methyl ester) *m*/*z* (CI) 174 (MH^+, 100) (EI) M^+ absent, 131, 114, 101, 59, 55, 43 (100)). In control experiments, they were proved to arise from oxidation of the 6-oxoheptanoic acid. [j] Reaction performed on 25 mmol of substrate. [k] Minor acidic products obtained were adipic acid (7%), heptanedioic acid (2.6%), 6-oxoheptanoic acid (4%), 4-oxooctanedioic acid (3%)[91] and 4-hydroxyoctanedioic acid γ-lactone (2%) (GC−MS (as methyl ester) *m*/*z* (CI) 187 (MH^+, 100) (EI) M^+ absent, 155, 126, 85 (100), 74, 59, 55). [l] Could be isolated 95% pure from the acid fraction by elution on column (2.8-cm diameter) of SiO_2 (100 g; $CHCl_3$/AcOH, 9.5:0.5; R_f 0.35). [m] 4-Hydroxydecanedioic acid γ-lactone (3%) was also formed (along with some succinic, glutaric, and adipic acids). GC−MS (as methyl ester) *m*/*z* (CI) 215 (MH^+, 100) (EI) M^+ absent, 183, 154, 141, 87, 85 (100), 74, 59, 55, 41. [n] GC−MS (as methyl ester) *m*/*z* (CI) 215 (MH^+, 100), (EI) 214 (M^+, 0.2), 196, 186, 164, 158, 143, 99, 71, 55, 43, 42, 41 (100). Was converted to 5-oxodecanedioic acid on further oxidation with **Ia**/H_2O_2.

path *b* of Scheme 1. (This Scheme, which for the sake of simplicity is limited to mono- and disubstituted olefins, $RCH{=}CHR^1$ where R = alkyl, aryl and R^1 = H, alkyl, will henceforth be referred to for the numbering of reactants and products.)

The reaction is believed to involve the formation of a 1,2-diol intermediate **3** upon acid hydrolysis of epoxide **2**, initially formed from olefin **1**. Diol **3** is then oxidized to α-hydroxy ketone (α-ketol) **4**, which undergoes C−C bond fission by hydrogen peroxide[20] leading ultimately to acids **8**, according to the reaction sequence previously reported by us[10b] for the tungsten-catalyzed oxidation of *vic*-diols to carboxylic acids with hydrogen peroxide under acidic conditions.

In principle, a similar pathway (path *b* of Scheme 1, henceforth referred to as the "hydrolytic" reaction pathway) might be plausible also in our two-phase process for olefins whose epoxides are easily opened by acids to yield diols (e.g., styrene and unsaturated five- to seven-membered rings). Indeed, when put into contact with water in a biphase system, catalyst **Ia** as a heteropolymetalate (in a peroxidic form) undergoes a partial degradation with the generation of enough acidity in the aqueous phase (determined as phosphoric and tungstic acid) to promote hydrolysis of the cited epoxides (see Experimental Section). However, this pathway as such seemed inadequate to us to account for the observed reactivity of medium- and long-chain alkenes (≥C_8) in view of the fairly good stability to hydrolysis exhibited by the corresponding epoxides under the same acidity conditions.

For this reason, we deemed it proper to address our investigation primarily to this group of alkenes to ascertain whether other reaction pathways leading to carboxylic acids from the first-formed epoxides were at work.

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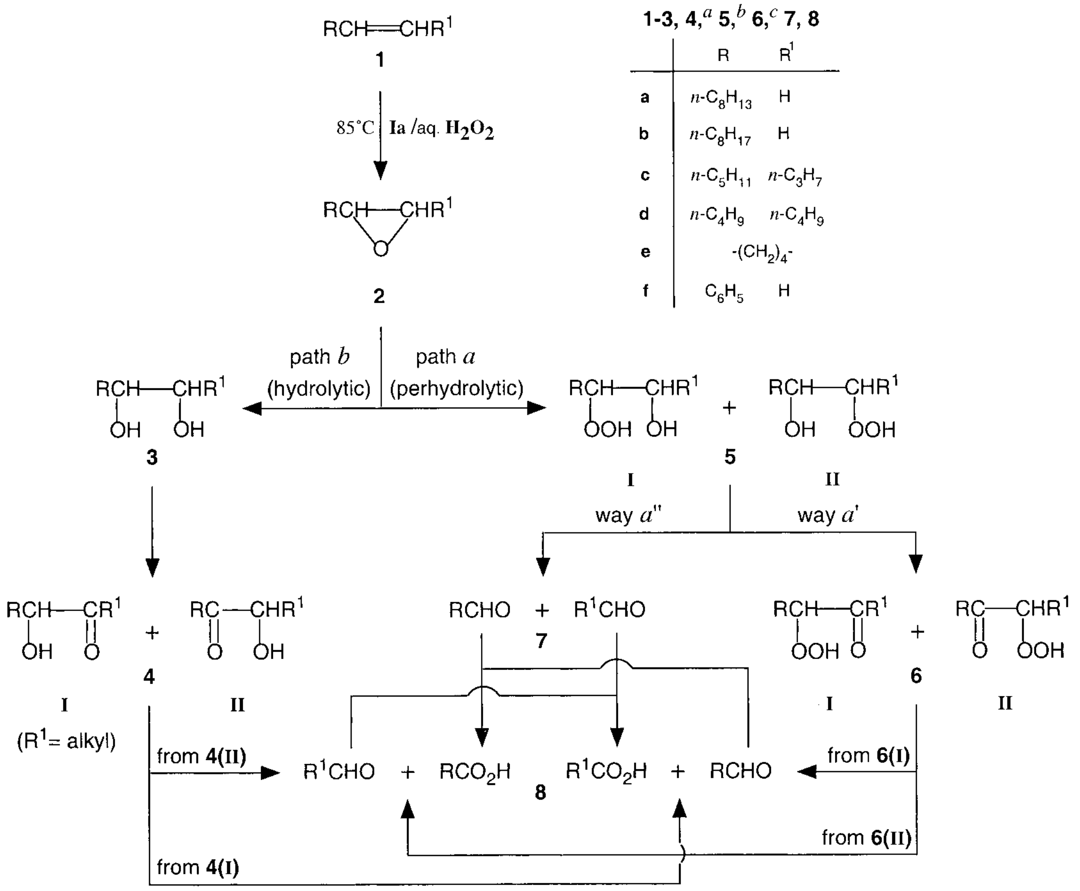
(20) (a) Recently, Ishii et al.[20b] reported the two-phase oxidation of internal 1,2-diols to α-diketones, via α-ketols, with 35% w/w H_2O_2 and complex $[\pi\text{-}C_5H_5N(CH_2)_{15}CH_3]_3\{PO_4[W(O)(O_2)_2]_4\}$ (PCWP) as the catalyst using 1,2-dichloroethane (4 L per mol of substrate) as the solvent. These authors also reported that α-diketones are cleaved to carboxylic acids by H_2O_2 under these conditions. Accordingly, it was stated that conversion of internal 1,2-diols into acids with PCWP/H_2O_2 takes place through the formation of the corresponding α-diketones under biphasic conditions. However, we have found that, under the two-phase conditions adopted (lack of the solvent), even with internal 1,2-diols the formation of carboxylic acids appears to proceed mainly through acid-catalyzed oxidative cleavage of the intermediate α-ketols by H_2O_2. This was proved by monitoring (by GC) the oxidation (60 °C) of 6-hydroxy-5-decanone (**4d**) (1 mmol) with **Ia** (0.01 mmol)/40% w/v H_2O_2 (3 mmol) at low conversion (18%, 1 h). Pentanal (**7d**), which forms in equimolar amounts with pentanoic acid (**8d**) from the oxidative cleavage of **4d**, was found to be present in the reaction mixture in a molar ratio of 1:1.75 to **8d** and of at least 20:1 to 5,6-decanedione. (b) Iwahama, T.; Sakaguchi, S.; Nishiyama, Y.; Ishii, Y. *Tetrahedron Lett.* **1995**, *36*, 1523.

Scheme 1[a]



1-3, 4,[a] 5,[b] 6,[c] 7, 8	R	R^1
a	*n*-C$_8$H$_{13}$	H
b	*n*-C$_8$H$_{17}$	H
c	*n*-C$_5$H$_{11}$	*n*-C$_3$H$_7$
d	*n*-C$_4$H$_9$	*n*-C$_4$H$_9$
e	-(CH$_2$)$_4$-	
f	C$_6$H$_5$	H

[a] β-Hydroxy aldehydes **4(I**; R^1 = H**)** could not be detected (see ref 24). [b]Compound **5IIf** was not formed (see text). [c]Compounds **6I** (R^1 = H**)** could not be detected (see text).

A. Medium- and Long-Chain Alkenes as Substrates. In conformity with above, we explored the **Ia**-catalyzed oxidation of some model epoxyalkanes under the reaction conditions (85 °C, molar ratio H_2O_2/epoxide = 5:1) at low oxidant conversion, with a view to detecting relevant intermediates. 1,2-Epoxyoctane (**2a**) and -decane (**2b**), among the terminal epoxyalkanes, and *trans*-4,5- and -5,6-epoxydecane (**2c** and **2d**), among the internal ones, were the epoxides of choice.

(a) Interrupted Oxidation of Epoxyalkanes with Ia/H_2O_2. Formation of β-Hydroperoxy Alcohols. The terminal epoxides **2a** and **2b** were examined first. In both cases, when the reaction was stopped (after 30 min,[21] with the epoxide conversion being almost quantitative for **2a** and 92−93% for **2b**), GC analysis showed a substantial presence of the aldehyde of one less carbon, **7a** (25%) and **7b** (33%),[22] which was accompanied by a small amount of the related final acid, **8a** (4%) and **8b** (2.3%).[23] Despite the aforementioned stability to hydrolysis of epoxides **2a,b** under the acidity conditions generated by catalyst **Ia** when put into contact with water in a two-phase system, the corresponding 1,2-diols **3a** and **3b**, indicative of the hydrolytic reaction pathway (Scheme 1, path *b*), were also found to form in considerable amounts (25% and 16%, respectively), together with their primary oxidation products α-ketols **4IIa** (9.5%) and **4IIb** (7.5%).[24] This result will be considered again for discussion in section IVA.

After silylation with *N*,*O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA), the peak of the aldehyde decreased dramatically while two new major components (43%, on the whole, in the first case and 50% in the second one), in ratios of approximately 2.7:1 (for **2a**) and 2:1 (for **2b**), appeared neatly in GC.[25] The characteristics of their GC−mass spectra (i.e., the presence of two silyl groups and the same molecular weight, 16 units higher than that of the corresponding diol) suggested the formation of regioisomeric C_8 and C_{10} β-hydroperoxy alcohols.

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[21] Five to six minutes for dropping hydrogen peroxide should be added (see Experimental Section).

[22] With the temperature of the injector set at 300 °C (carrier gas, He). At 250 °C, the formation of the aldehyde decreased by more than 50%. This suggested the decomposition of a parent compound occurring in the gas chromatograph (see ahead in the text).

[23] The coproduced formic acid was revealed by ionic chromatography of the water phase.

[24] α-Hydroxy aldehydes **4Ia** and **4Ib** could not be detected. However, small amounts of the corresponding aldehydes of one less carbon, suggesting an early formation of the former, were found (along with α-ketols **4IIa** and **4IIb**) when diols **3a,b** were oxidized with **Ia**/H_2O_2 under two-phase conditions at low conversion using $CHCl_3$ as the solvent (to minimize further oxidation of the α-ketol; cf. ref 20). Thus, on reacting 1,2-decanediol (**3b**) (5 mmol) in $CHCl_3$ (25 mL) for 5 h at reflux with **Ia** (0.05 mmol)/40% w/v H_2O_2 (25 mmol), a molar ratio of 1-hydroxy-2-decanone to nonanal of about 11:1 was found (by GC) at 22% conversion of the diol. Nonanoic acid was formed only in negligible amounts (molar ratio C_9 acid to C_9 aldehyde = 1:5).

[25] Other minor components were also detected by GC. Their GC−mass spectra were consistent with the structures of β,β'-dihydroxyalkyl (C_8, C_{10}) peroxides and ethers. They presumably result from further reaction of, respectively, the β-hydroperoxy alcohols (see ahead in the text) and *vic*-diols previously formed with the respective starting epoxides.

The two components (nonsilylated) were revealed in TLC as a single spot. Their isolation by column chromatography gave an oily product, whose ^{1}H and ^{13}C NMR spectra confirmed it to be a mixture of 2-hydroperoxy-1-octanol (**5Ia**) or -decanol (**5Ib**) (major component) and 1-hydroperoxy-2-octanol (**5IIa**) or -decanol (**5IIb**), respectively, in the ratios indicated above. Attempts to obtain specimens of the individual components from the mixture were unsuccessful. Nevertheless, the formed regioisomers **5IIa** and **5IIb** were compared with pure samples separately obtained by the addition of alkaline hydrogen peroxide to the appropriate epoxides (see Experimental Section).

When injected (as a 0.5–2% ethereal solution) into the gas chromatograph, the isolated mixed 2(1)-hydroperoxy-1(2)-octanols **5a** and -decanols **5b** decomposed, forming the previously observed aldehydes.[27] β-Hydroperoxy alcohols are known to undergo thermal[27] as well as acid-[29,30] and base-catalyzed[26] decomposition to carbonyl compounds.

The interrupted oxidation of the internal epoxyalkanes *trans*-**2c,d** with **Ia**/H_2O_2 showed a similar trend. After 1 h,[21] the corresponding β-hydroperoxy alcohols **5c (I + II)**[31] and **5d** were found to be formed in an approximately 1:1.3 molar ratio[32] to the respective 1,2-diol[33]/α-ketol[34] pairs (where the α-ketol was the major component), together with appreciable amounts of aldehydes **7c** and **7d** and related acids (**8c** and **8d**).

As compared with the terminal epoxyalkanes **2a,b**, the rate of disappearance of the epoxide (as followed by GC) was in these cases considerably slower.[35a] For instance, whereas conversion of 1,2-epoxydecane (**2b**) reached over 90% after 30 min,[21] conversion of *trans*-4,5- and -5,6-epoxydecane (**2c** and **2d**) was less than 30% after 1 h under the same conditions. This circumstance, combined with the fact that the resulting β-hydroperoxy alcohols **5c**,**d** are quite reactive under the reaction conditions (see section III), prevented an adequate accumulation of the desired intermediates, rendering their isolation rather laborious. The inconvenience, however, could be overcome by the use of more concentrated H_2O_2 (70% w/w) and a lower temperature. NMR data of the isolated products thus obtained confirmed the identities of 5-hydroperoxy-4-decanol (**5Ic**) and 4-hydroperoxy-5-decanol (**5IIc**), present in about a 1:1 ratio, and of 6-hydroperoxy-5-decanol (**5d**). These compounds were assigned the *erythro* configuration on the basis of their reduction with triphenylphosphine to the corresponding *vic*-diols.

It should be noted that when the parent alkenes **1a**–**d** were subjected to interrupted-oxidation experiments with **Ia**/H_2O_2 in place of epoxides **2a**–**d** under identical conditions, qualitatively analogous results were obtained, thus confirming the intermediacy of the epoxide in the early stage of the reaction beyond any reasonable doubt. In these experiments, however, when the reaction was stopped (with the olefin conversion reaching 90–99%), the value of the product ratio of diol + ketol versus β-hydroperoxy alcohol was in general higher than that found from the corresponding epoxide. This suggests that a competitive tungsten-catalyzed epoxidation of alkene **1** by the formed β-hydroperoxy alcohol **5**, with concomitant production of diol **3**,[28] occurs in our process, the extent of the reaction depending on the nature of the substrate and related intermediates (epoxide and β-hydroperoxy alcohol). For the sake of clarity, this reaction has been omitted in Scheme 1.

(b) Perhydrolytic versus Hydrolytic Reaction Pathway. When caused to react with **Ia**/H_2O_2 under the reaction conditions, the isolated β-hydroperoxy alcohols **5a**–**d** were readily converted into the corresponding carboxylic acids **8a**–**d**. Thus, a reaction pathway leading to acids **8** from olefins **1** via β-hydroperoxy alcohols **5** (Scheme 1, path *a*) appears to be operative in our process for the group of substrates under study as an alternative to the pathway via 1,2-diols **3** (Scheme 1, path *b*). Clearly, hydrogen peroxide is directly involved in this pathway (henceforth referred to as "perhydrolytic" reaction pathway), being responsible for the formation of **5** by nucleophilic attack at the oxirane carbon of **2**.

It should be observed that the easy formation of **5** in our process by perhydrolysis of **2** indicates that peroxocomplex **Ia** does not intervene on **2** as an "oxidation" catalyst (oxidative cleavage of the epoxide to carbonyl compounds) to any appreciable extent. Although early-transition-metal peroxocomplexes have been reported to effect such a cleavage catalytically (with H_2O_2 as the terminal oxidant)[36] in addition to stoichiometrically,[36,37] the reactivity of this class of complexes toward epoxides (to give carbonyl compounds) according to what is observed with **Ia** appears far lower than that exhibited by hydrogen peroxide (to give β-hydroperoxy alcohols) under the reaction conditions adopted.

Nevertheless, catalyst **Ia** is important in this stage of the reaction, providing electrophilic assistance to the epoxide opening by hydrogen peroxide/water mainly as a Brönsted acid through the acidic species that arise, as already mentioned, from its partial hydrolytic degradation. Indeed, ring opening of epoxyalkanes **2a**–**d** failed when carried out in the presence of aqueous hydrogen peroxide (neutral) only.

Of course, between the hydrolysis and perhydrolysis of the epoxyalkane a competition exists, which under the two-phase conditions adopted is governed by the greater

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(26) Ogata, Y.; Sawaki, Y.; Shimizu, H. *J. Org. Chem.* **1978**, *43*, 1760.

(27) Small amounts of *vic*-diols **3a,b** and α-ketols **4IIa,b** were also formed.

(28) Mattucci, A. M.; Perrotti, E.; Santambrogio, A. *J. Chem. Soc., Chem. Commun.* **1970**, 1198.

(29) Adam, W.; Rios, A. *J. Chem. Soc., Chem. Commun.* **1971**, 822.

(30) Subramanyam, V.; Brizuela, C. R.; Soloway, A. H. *J. Chem. Soc., Chem. Commun.* **1976**, 508.

(31) As silyl derivatives, **5Ic** and **5IIc** eluted together in GC. The presence of the two regioisomers, however, could be detected from the analysis of the GC–mass spectrum (see Experimental Section).

(32) The found value of the molar ratio (in favor of the 1,2-diol/α-ketol pair) is misleading because of the high reactivity of β-hydroperoxy alcohols **5c,d** under the reaction conditions (see section III).

(33) (a) The formed diols were identified as *erythro*-4,5-decanediol and *meso*-5,6-decanediol, respectively, by comparison with authentic samples.[33b] (b) Abe, Y.; Matsumura, S.; Shibuya, Y. *Yukagaku* **1979**, *28(4)*, 276.

(34) A nearly 1:1 regioisomeric mixture of 5-hydroxy-4-decanone (**4Ic**) and 4-hydroxy-5-decanone (**4IIc**) was obtained from the epoxide *trans*-**2c**, as determined by GC and GC–MS (after silylation with BSTFA). Regioisomer **4Ic** eluted first.

(35) (a) Long-chain α-epoxides have been reported to undergo ring opening by nucleophiles (e.g., MeOH) faster than the internal ones under homogeneous conditions.[35b] As amphiphiles, in the present two-phase system, the former should be regarded as being more suitably oriented than the latter to contact their polar head with the nucleophiles water and hydrogen peroxide. This might contribute to their much faster hydrolysis/perhydrolysis. (b) Bischoff, M.; Zeidler, U.; Baumann, H. *Fette, Seifen, Anstrichm.* **1977**, *79*(3), 131.

(36) Bonchio, M.; Conte, V.; Di Furia, F.; Modena, G. *J. Mol. Catal.* **1991**, *70*, 159.

(37) Záhoni-Budó, E.; Simándi, L. *Inorg. Chim. Acta* **1987**, *134*, 25.

or lesser lipophilic character of the epoxide involved and the nature of the acid catalyst, in addition to the concentration of the hydrogen peroxide used and the relative reactivity of the two nucleophiles, hydrogen peroxide and water, intervening in the oxirane opening (see section IVA). Accordingly, the perhydrolytic pathway (path *a*) appears to be the major route for the present two-phase oxidation of medium- and long-chain alkenes to carboxylic acids. It can be expected, however, that with lower aliphatic alkenes ($<C_8$) the alternative hydrolytic pathway (path *b*) operates to a larger extent.

B. Arylalkenes and Cycloalkenes as Substrates. In light of the results attained, we wondered whether the perhydrolytic reaction pathway might play some role also with arylalkenes and C_5-C_7 cycloalkenes, whose oxidation to acids we at first assumed to follow the hydrolytic reaction pathway on the basis of the known good-to-high susceptibility to acid hydrolysis of the respective epoxides.

To answer this question, the representative cyclohexene and styrene oxides, **2e** and **2f**, were subjected to interrupted-oxidation experiments with **Ia**/H_2O_2, as had previously been done with epoxyalkanes **2a**−**d**. In both cases when the reaction was stopped (after 10 min),[21] together with the expected 1,2-diol/α-ketol pair (*trans*-**3e**/**4e** and **3f**/**4IIf**, respectively) as main products (66% for **2e** and 78% for **2f** on the whole, where the 1,2-diol was the major component), GC analysis after silylation revealed the formation of the corresponding *β*-hydroperoxy alcohols **5e** (16%) and **5If** (5%),[38] which were identified by GC-MS.

Operating at ambient temperature (instead of 85 °C), these compounds could be obtained in somewhat higher yields (21−22%), which made their isolation easier. NMR data of the isolated products confirmed the identities of 2-hydroperoxycyclohexanol (**5e**) and 2-hydroperoxy-2-phenylethanol (**5If**). The former compound was assigned the *trans* configuration on the basis of its reduction to glycol with triphenylphosphine. It is noteworthy that, at variance with the terminal epoxides **2a**,**b**, from perhydrolysis of **2f** only the regioisomer bearing the hydroperoxy group on the most-substituted carbon atom ("abnormal" product)[39] was obtained. The selective formation of the "abnormal" isomer from terminal epoxides and hydrogen peroxide has been observed in neutral[29] or acidic[28,30] nonaqueous media.

As expected, compounds **5e**,**f**, like the other *β*-hydroperoxy alcohols examined, were easily converted upon treatment with **Ia**/H_2O_2 into the corresponding carboxylic acids **8e**,**f**. These results thus indicate that also for the above alkenes the perhydrolytic reaction pathway is operative in our process, although to a modest extent compared to the hydrolytic one, which remains highly favored.

With regard to the cycloalkene-to-acid oxidation with **Ia**/H_2O_2, some additional comment is appropriate about the poor results obtained with unsaturated medium rings (e.g., eight- and ten-membered) as contrasted with the good-to-excellent results obtained with unsaturated common rings (five- to seven-membered) (cf. section I). This difference is undoubtedly to be attributed to the anomalous behavior of the related intermediate 1,2-epoxides in the ring-opening step. Indeed, transannular reactions, which are known[40] to occur upon the opening of medium-sized ring cycloalkene oxides under acidic conditions, readily take place in the presence of the acidity provided by the catalyst hydrolysis and seriously compete with or prevail on the direct nucleophilic attack by hydrogen peroxide or water, thus making the obtainment of the desired acids difficult and highly unselective.

III. The Perhydrolytic Reaction Pathway. Transformation of the *β*-Hydroperoxy Alcohol Intermediates into Carboxylic Acids. As already mentioned, *β*-hydroperoxy alcohols **5** are susceptible to decomposition with the formation of carbonyl compounds.[28−30] On the other hand, bearing a hydroxy function, they also would be expected to undergo oxidation in the presence of **Ia**/H_2O_2, since this system is known to oxidize alcohols to carbonyl and carboxylic compounds.[17] Relative to the study of the perhydrolytic pathway of our process, we deemed it interesting to ascertain whether these modes of reaction were both operative and to determine the extent of each in the conversion of intermediates **5** into carboxylic acids **8** with **Ia**/H_2O_2, reported in section II for the isolated compounds **5a**−**f**.

In one case (initial oxidation of the *β*-hydroperoxy alcohol), transformation **5** → **8** implies the formation of the carbonyl derivative **6**. Decomposition of **6** to the aldehyde and carboxylic acid followed by oxidation of the former then affords the final acids **8** (Scheme 1, path *a*, way *a′*). In the other case (initial decomposition of the *β*-hydroperoxy alcohol), transformation **5** → **8** proceeds through the oxidation of the resultant aldehydes **7** (Scheme 1, path *a*, way *a″*).

An investigation of the two ways, *a′* and *a″*, potentially involved in the above transformation was undertaken by monitoring (by GC or HPLC) the progress of the conversion into acids **8** of some *β*-hydroperoxy alcohols **5** significantly representative of the perhydrolytic pathway of our process. Accordingly, compounds **5Ib** (isolated admixed with **5IIb**), **5IIb** (obtained pure apart), and **5d** were utilized for this study, as models of terminal (with a primary (**5Ib**) or secondary (**5IIb**) hydroxy group) and nonterminal (**5d**) *β*-hydroperoxy alcohols. By "terminal" or "nonterminal" *β*-hydroperoxy alcohol we mean the one deriving from a terminal or an internal epoxide, respectively. Referring to their initial step, way *a′* and way *a″* will henceforth be concisely denoted as the "oxidation" and "decomposition" ways, respectively.

A. The Oxidation and Decomposition Ways (*a′* and *a″*). For a better understanding of the following part the reader is referred to Schemes 2 and 3. These provide a more detailed picture of ways *a′* and *a″* (not included in Scheme 1 for the sake of simplicity) relative to the examined model *β*-hydroperoxy alcohols **5d** and **5IIb**, respectively, which lent themselves to an easier or cleaner determination of the products resulting from the two ways. The third compound examined, **5Ib**, is discussed later.

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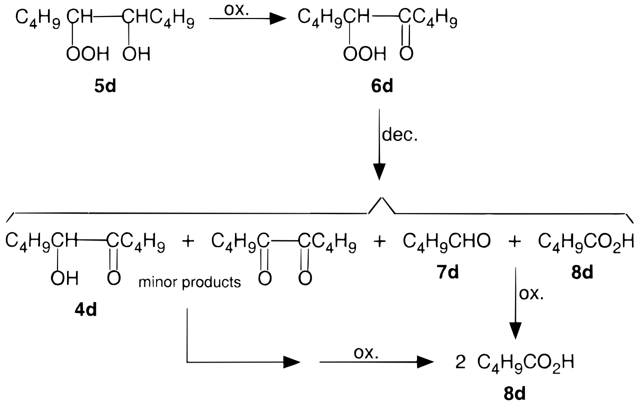
[38] The molar ratio of 2-hydroperoxy-2-phenylethanol (**5If**) versus 1-phenyl-1,2-ethanediol (**3f**) + phenacyl alcohol (**4IIf**) changed from 1:15 to 1:5.5 when styrene (**1f**), rather than its oxide **2f**, was subjected to interrupted-oxidation experiments with **Ia**/H_2O_2 under the same conditions. This is due to the fact that, starting from **2f**, heating of the substrate/catalyst **Ia**/water mixture prior to addition of hydrogen peroxide according to the procedure adopted (cf. Experimental Section) favors an early hydrolysis of the epoxide.

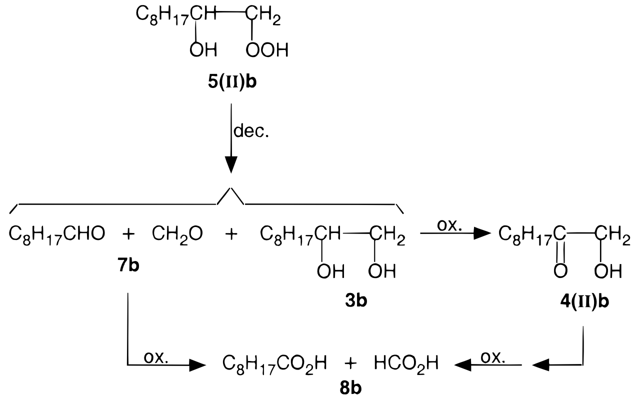
[39] For a definition of "normal" and "abnormal" product with regard to the direction of ring opening by a nucleophile in unsymmetrical epoxides, see: Parker, R. E.; Isaacs, N. S. *Chem. Rev.* **1959**, 742 and references therein.

[40] Cope, A. C.; Martin, M. M.; McKervey, M. A. *Q. Rev.* (*London*) **1966**, *20*, 119 and references therein.

Scheme 2. Course of Way *a′* for β-Hydroperoxy Alcohol 5d



Scheme 3. Course of Way *a″* for β-Hydroperoxy Alcohol 5IIb[a]



[a] For **5d** the α-ketol can arise directly from decomposition of the β-hydroperoxy alcohol, in addition to the 1,2-diol oxidation.

(a) β-Hydroperoxy Alcohols Bearing a Secondary Hydroxy Group. Predominance of Way *a′*: Formation of α-Hydroperoxy Ketones. Proceeding with the nonterminal β-hydroperoxy alcohol **5d** as indicated above, we observed (by GC) a facile formation of the corresponding α-hydroperoxy ketone **6d**,[41] which was identified by GC−MS. The yield of **6d** was found to pass through a maximum value (82% at 40% conversion of **5d**) and then to decrease after the reaction had proceeded for a time, with the concomitant progressive increase of the final acid **8d**. The α-hydroperoxy ketone structure was confirmed by NMR and IR spectra of the isolated product as well as by its reduction with triphenylphosphine to the corresponding α-ketol. When heated (85 °C, under helium) in the presence of water, the isolated 6-hydroperoxy-5-decanone (**6d**) decomposed readily, affording pentanal (**7d**) and pentanoic acid (**8d**) in nearly equimolar amounts, along with small quantities of 6-hydroxy-5-decanone (**4d**, 3%) and 5,6-decanedione (1.5%). The latter compounds, like the aldehyde **7d**, are easily converted into the acid **8d** under the reaction conditions (Scheme 2).

Interestingly, the decomposition of **6d** occurred much more slowly if carried out in the presence of hydrogen peroxide (40% w/v) and was accelerated by the addition of the metal catalyst. In the presence of the latter, decomposition took place (though very slowly and much more consistently if the water phase was omitted) even under milder conditions (35 °C) where thermolysis occurred only to a negligible extent. Under these conditions, the above-mentioned α-ketol and α-diketone byproducts, indicative of a radical pathway,[42b,c] were observed as well.

These observations suggest that the decomposition of the α-hydroperoxy ketone intermediate promoted by tungsten complex **Ia**, like the thermal one, proceeds homolytically. The tungsten-catalyzed homolytic decomposition of hydroperoxides has been reported.[43] The α-hydroperoxy ketone homolysis may be somewhat complicated because of competitive acid-catalyzed heterolysis due to both the organic acid, which accumulates during the decomposition,[42a] and the Brönsted acid activity of catalyst **Ia** (see section IVA). Thermal, redox (Fe^{2+}, Mn^{2+}), and acid-promoted decompositions of α-hydroperoxy ketones and related mechanisms have been previously investigated.[42]

Operating with the terminal β-hydroperoxy alcohol **5IIb** in a way analogous to that followed for **5d**, we were able to evidence the formation of the corresponding primary α-hydroperoxy ketone **6IIb**. Rather notably, compounds of this kind have not been hitherto observed.

At variance with the secondary α-hydroperoxy ketone **6d**, detection of the primary **6IIb** was possible by GC (cold on-column injector) only with some difficulty because of its greater instability;[44] however, this did not prevent identification by GC−MS. On the contrary, this compound could be easily revealed by HPLC, and liquid chromatography/thermospray−mass spectrometry (LC/TSP(MS) analysis confirmed the molecular weight. The structure in any case was unambiguously established by reduction with triphenylphosphine to the corresponding α-ketol.

It is worthwhile that silylation with BSTFA (even in the absence of pyridine) of 1-hydroperoxy-2-decanone (**6IIb**) in the reaction mixture did not lead to the corresponding silyl derivative to any appreciable extent (as revealed by GC−MS analysis) but essentially to the addition product at the aldehydic carbonyl group of the α-keto aldehyde expected to form from decomposition of the former.[45] The reaction of nonenolizable carbonyl compounds with silylating agents under nucleophilic catalysis conditions is known.[46]

The yield of the α-hydroperoxy ketone **6IIb** (analyzed as α-ketol), like that of **6d**, passed through a maximum

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[41] In addition to detection as the silyl derivative (for details, see Experimental Section), **6d** could also be revealed as such by GC (cold on-column injector), without appreciable decomposition. Its formation during the progress of transformation **5d** → **8d** was quantitated by GC as the α-ketol, after reduction in situ with triphenylphosphine.

[42] (a) Pritzkow, W. *Chem. Ber.* **1955**, *58*, 572. (b) Pinkus, A. G.; Haq, M. Z.; Lindberg, J. G. *J. Org. Chem.* **1970**, *35*, 2555 (c) Sawaki, Y.; Ogata, Y. *J. Org. Chem.* **1976**, *41*, 2340 (d) Sawaki, Y., Ogata, Y. *J. Am. Chem. Soc.* **1978**, *100*, 856.

[43] Sheldon, R. A.; Van Dorn, J. A. *J. Catal.* **1973**, *31*, 427 and references therein.

[44] This is in line with the fact that secondary α-hydroperoxy ketones in turn exhibit thermal as well as hydrolytic lability much higher than the tertiary ones.[47b.]

[45] Analogously, under the same conditions the silyl derivative of the secondary α-hydroperoxy ketone **6d** was found to gradually convert into the corresponding α-diketone (see Experimental Section).

[46] (a) Birkofer, L.; Ritter, A. *Angew. Chem., Int. Ed.* **1965**, *4*, 417. (b) Nakamura, E.; Shimizu, M.; Kuwajima, I. *Tetrahedron Lett.* **1976**, 1699. (c) Furin, G. G.; Vyazankina, O. A.; Gostevsky, B. A.; Vyazankin, N. S. *Tetrahedron* **1988**, *44*, 2675. (d) Kozyukov, V. P.; Kozyukov, Vik. P.; Mironov, V. F. *Zh. Obshch. Khim.* **1982**, *52*(6), 1386; *Chem. Abstr.* **1982**, *97*, 163077. (e) Kuvajima, I.; Nakamura, E. *Acc. Chem. Res.* **1985**, *18*, 181.

value (78%) which, however, was obtained at a much lower conversion of the β-hydroperoxy alcohol (17% instead of 40%), owing to the slower oxidation of the latter combined with the faster decomposition of the resulting oxo derivative (see above).

To the best of our knowledge, these are the first examples of α-hydroperoxy ketones obtained by metal-catalyzed oxidation of β-hydroperoxy alcohols with hydrogen peroxide. α-Hydroperoxy ketones (secondary and tertiary) are usually prepared by autoxidation of aliphatic ketones at 100 °C in the absence of catalysts[47] and at or below 0 °C in the presence of strong bases.[48]

Following the progress of the transformation of 1-hydroperoxy-2-decanol (**5IIb**) into acids with **Ia**/H_2O_2, we found the aldehyde of one less carbon, nonanal (**7b**), to be formed together with 1-hydroperoxy-2-decanone (**6IIb**) (6% at 17% conversion of **5IIb**, corresponding to the maximum yield (78%) for intermediate **6IIb**, as mentioned above). Since the C_9 aldehyde cannot come from fragmentation of **6IIb**, which leads to formaldehyde and nonanoic acid, this result unequivocally shows that the decomposition way *a″* is operative, together with the oxidation way *a′*, for compound **5IIb** (Scheme 3).

Evidence of way *a″* through the formation of the aldehyde could also be gained indirectly for the nonterminal β-hydroperoxy alcohol **5d**. It was based on the value of the aldehyde-to-carboxylic acid molar ratio at partial conversion of **5d**, which was found to be higher than unity; it would be expected to be less if only way *a′* were operative, considering that the formed aldehyde oxidizes under the reaction conditions. In fact, on decomposition (way *a″*) 6-hydroperoxy-5-decanol (**5d**) gives rise to two molecules of C_5 aldehyde while it affords one molecule of C_5 aldehyde and one of C_5 acid on oxidation, through cleavage of the resulting α-hydroperoxy ketone **6d** (way *a′*). At 40% conversion of **5d**, corresponding to the maximum yield (82%) for intermediate **6d** (see above), the value of this ratio indicated the presence of about 8% of pentanal ascribable to the decomposition (4%) of **5d**.

It should be pointed out that the aforementioned formation (6%) of nonanal (**7b**), observed at low conversion (17%) of 1-hydroperoxy-2-decanol (**5IIb**), was accompanied by that of 1,2-decanediol (**3b**, 4.5%) and 1-hydroxy-2-decanone (**4IIb**, 3%) (Scheme 3). The presence of the corresponding 1,2-diol **3d** (in a very small amount) and α-ketol **4d** (3%) was likewise observed with the β-hydroperoxy alcohol **5d** (at 40% conversion). These products, like the aldehyde, have to be regarded as indicative of the decomposition of hydroperoxide compounds, such as **5IIb** and **5d**,[49] and contribute to formation of the final carboxylic acid by way *a″*.

This view is supported by the results of blank decomposition experiments with the above β-hydroperoxy alcohols under the reaction conditions. When heated (85 °C, under helium) admixed with catalyst **Ia** in the presence of the aqueous phase but in the absence of the oxidant hydrogen peroxide, compounds **5IIb** and **5d** gave rise to the respective 1,2-diols **3b** and **3d** along with the expected aldehydes. In the case of **5d**, bearing a secondary hydroperoxy group, the corresponding α-ketol **4d** was also formed.

The above findings, while proving the occurrence of ways *a′* and *a″* for both nonterminal (R, R^1 = alkyl) and type **II** terminal (R = alkyl, R^1 = H) β-hydroperoxy alcohols **5** such as **5d** and **5IIb**, clearly point to the predominance of way *a′* for these classes of compounds. On the basis of the maximum yield found with **5IIb** and **5d** for the α-hydroperoxy ketone intermediate (also taking into account, on one hand, the associated cleavage products and, on the other, the competitively produced aldehyde, 1,2-diol, and α-ketol), we can estimate that for the substrates in question the final carboxylic acids pertaining to transformation **5** → **8** come from the oxidation way *a′* to the extent of at least 85%. This figure is likely to actually be a little lower if one takes into account that the intermediates formed by the alternative way *a″* are in part oxidized during the experiment.

(b) β-Hydroperoxy Alcohols Bearing a Primary Hydroxy Group. Comparable Contribution of Ways *a′* and *a″*. In light of these results, no doubt also with type **I** terminal (R = alkyl, R^1 = H) β-hydroperoxy alcohols **5**, such as 2-hydroperoxy-1-decanol (**5Ib**), ways *a′* and *a″* are both operative. In this case, however, monitoring (by GC or HPLC) the progress of the transformation of **5Ib** into acids with **Ia**/H_2O_2, we were not able to evidence the formation of the relative intermediate diagnostic of the oxidation way *a′*, α-hydroperoxy aldehyde **6Ib**. This may be due to the very high instability of such compounds,[50] which justifies the fact that, to our knowledge, no authentic example of α-hydroperoxy aldehyde has so far been reported. Moreover, it was also impossible to distinguish the aldehyde formed (together with the 1,2-diol and α-ketol) by the alternative way *a″*, through decomposition of **5Ib**, since the same aldehyde (other than formaldehyde) can also be generated by way *a′* through cleavage of **6Ib**. This situation, while not allowing us to give a precise picture of way *a′* for the compounds under study, also makes it rather difficult to assess the relative importance of the two ways for these compounds.

However, if we consider the fact that from comparative experiments primary alcohols appear to be over three times less oxidizable than the secondary ones by **Ia**/H_2O_2 under the reaction conditions, we can also reasonably expect 1-hydroxy-2-hydroperoxy derivatives **5I** (R = alkyl, R^1 = H) to exhibit an analogous behavior toward oxidation with respect to their 2-hydroxy-1-hydroperoxy isomers **5II.** Thence, we would expect the former to be more available than the latter to be converted into acids by the alternative decomposition way *a″*, the stability of the

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[47] (a) Sharp, D. B.; Patton, L. W.; Whitcomb, S. E. *J. Am. Chem. Soc.* **1951**, *73*, 5600. (b) Sharp, D. B.; Whitcomb, S. E.; Patton, L. W.; Moorhead, A. D. *J. Am. Chem. Soc.* **1952**, *74*, 1802.

[48] (a) Cubbon, R. C. P.; Hewlett, C. *J. Chem. Soc. C* **1968**, 2978. (b) Sawaki, Y.; Ogata, Y. *J. Am. Chem. Soc.* **1975**, *97*, 6983.

[49] At variance with **5d**, in the case of **5IIb** bearing a primary OOH group the found α-ketol cannot originate directly from decomposition of the β-hydroperoxy alcohol (H-abstraction reaction). Its formation has to be ascribed to oxidation of the previously formed 1,2-diol by **Ia**/H_2O_2. In any case, it speaks for way *a″* as well. A priori, we cannot exclude, for both **5IIb** and **5d**, that the found α-ketol may in part arise also from decomposition of the corresponding α-hydroperoxy ketone formed by the alternative way *a′* (cf. text and Scheme 2 for the case of **5d**). However, since (*i*) the figures considered refer to experiments at low/partial conversion, where the intermediate α-hydroperoxy ketone formed is present to the extent of 78–82%, and (*ii*) decomposition of the latter leads only to minor amounts of α-ketol (cf. text and Scheme 2 for the case of **6d**), the possible contribution of way *a′* to the formation of the found α-ketol (due to the decomposed α-hydroperoxy ketone) is insignificant.

[50] Baader, W. J.; Bohne, C.; Cilento, G.; Dunford, H. B. *J. Biol. Chem.* **1985**, *260*, 10217.

two types of compounds under the reaction conditions being nearly the same as ascertained in control experiments with **5Ib** and **5IIb**.[51] Thus, the contribution of way *a″*, estimated at about 15% for terminal (R = alkyl, R^1 = H) β-hydroperoxy alcohols **5** of type **II** on the basis of the data obtained for **5IIb**, should reach much higher values (around 50%) with analogous compounds of type **I**.

B. Medium Effect on Transformation 5 → 8. In addition to the structural factors of β-hydroperoxy alcohols **5** (the presence of a primary rather than secondary hydroxy group), the reaction medium certainly also affects the extent to which way *a″* operates in the reaction. This emerges from the results of blank decomposition experiments with compounds **5IIb** and **5d** performed under conditions different from the standard ones (which implied the presence of both catalyst **Ia** and water, as reported above and in the Experimental Section). Indeed, whereas decomposition of **5IIb** and **5d** was found to occur much faster when the aqueous phase was omitted, on the contrary it took place much more slowly in the presence of water alone (without the metal catalyst) and even more slowly when water was replaced with hydrogen peroxide (40% w/v). It thus turns out that hydrogen peroxide exerts a stabilizing action on the β-hydroperoxy alcohol, analogous to that exerted on the α-hydroperoxy ketone. Furthermore, water retards decomposition of the β-hydroperoxy alcohol by the metal catalyst, likely by complexing with the latter.[52] The retarding effect of the aqueous medium should, of course, be greater under the actual reaction conditions due to the presence of hydrogen peroxide which, as a better nucleophile than water,[53] competes more efficiently with the β-hydroperoxy alcohol for coordination sites on the metal.

As to the nature of the decomposition of **5** under the reaction conditions, the results of the relative blank experiments suggest that a homolytic process (thermal and metal-induced) is mainly involved, analogously to the previously discussed decomposition of α-hydroperoxy ketones. Also in this case, however, an alternative acid-catalyzed heterolysis of **5** may occur to some extent under the acidity conditions of the reaction (see section IVA).

C. Minor Reactions in Transformation 5 → 8: Formation of β-Hydroxyperoxyhemiacetals. As we have seen, transformation **5** → **8** is the result of intertwining oxidation and decomposition reactions following ways *a′* and *a″*. Actually, side reactions may further complicate the course. Indeed, as results from blank experiments, aldehyde **7** (which in transformation **5** → **8** originates from **5** by both way *a′* and way *a″*) can react with the β-hydroperoxy alcohol itself to give β-hydroxyperoxyhemiacetal **9** (eq 1, where R^2 and R^3 = alkyl and H, alkyl, respectively, or vice versa and R^4 = H, alkyl stand for R or R^1 of Scheme 1). Adduct **9** then decomposes on heating into carboxylic acid **8** and α-hydroxy carbonyl compound **4** with evolution of hydrogen (eq 2), according to a pattern amenable to the previously reported[53] thermolysis of peroxyhemiacetals, leading to acids and aldehydes.

$$\underset{\mathbf{5}}{R^2CH(OOH)CH(OH)R^3} + \underset{\mathbf{7}}{R^4CHO} \rightleftharpoons \underset{\mathbf{9}}{R^4CH(OH)OOCH(R^2)CH(OH)R^3} \qquad (1)$$

$$\mathbf{9} \xrightarrow[-H_2]{\Delta} \underset{\mathbf{8}}{R^4CO_2H} + \underset{\mathbf{4}}{R^2COCH(OH)R^3} \qquad (2)$$

As a matter of fact, after subjecting β-hydroperoxy alcohols **5IIb** and **5d** to blank decomposition experiments, appreciable amounts of the corresponding adducts **9** (R^2, R^4 = H, R^4 = n-C_8H_{17} and R^2 = H, R^3, R^4 = n- C_8H_{17} in the former case, R^2, R^3, R^4 = n-C_4H_9 in the latter) were detected. Likewise, the carboxylic acids **8b** and **8d** related to the expected aldehydes **7b** and **7d** invariably formed, along with the above-mentioned 1,2-diols and α-ketols. It has to be observed, however, that the equilibrium of eq 1, as ascertained in control experiments, is markedly shifted to the left in the presence of excess hydrogen peroxide, which interacts with the aldehyde to form adducts[54] and the corresponding acid. It follows that the actual contribution of the "β-hydroxyperoxyhemiacetal" route to the formation of carboxylic acids **8** (and associated precursors **4**) from β-hydroperoxy alcohols **5** is negligible in our process.

IV. Factors Conditioning the Reaction. In addition to the solvent mentioned at the beginning, another factor influences the course of the reaction: the hydrogen peroxide concentration. As to the perhydrolytic pathway, the importance of this factor is readily understandable, because the activity of hydrogen peroxide as a nucleophile in the oxirane-opening step (to give the β-hydroperoxy alcohol) depends on its concentration. Less apparent is the fact that the oxirane opening by water, which initiates the alternative hydrolytic pathway, is also indirectly affected by the hydrogen peroxide concentration. This aspect will now be discussed.

A. Hydrogen Peroxide Concentration and Medium Acidity. Implications for the Oxirane-Opening Step. Studying the course of the oxidation of medium- and long-chain alkenes to carboxylic acids with **Ia**/H_2O_2 (section IIA), we found that the interrupted oxidation of the intermediate epoxyalkanes under the two-phase reaction conditions (performed on C_8 and C_{10} model compounds), in addition to affording the respective β-hydroperoxy alcohols (major product), also leads to substantial amounts of the corresponding hydrolysis products (1,2-diols and their primary oxidation products, α-ketols).

The situation, however, is quite different if the above reaction is carried out with 16% instead of 40% w/v hydrogen peroxide, other conditions being equal. In this case, the formation of the 1,2-diol (and thence of the α-ketol) is considerably slowed, as is that of the β-hydroperoxy alcohol. The effect of the concentration of hydrogen peroxide used (16% and 40% w/v) on the hydrolysis of 1,2-epoxyoctane (**2a**) and -decane (**2b**), when the latter are put into contact under stirring with the **Ia**/H_2O_2 two-phase system (procedure A), is shown in Table 2 (runs 1−4).

The observation that in the above experiments epoxyalkanes **2a,b** exhibit a different aptitude to hydrolysis

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(51) In comparative experiments carried out in the presence of catalyst **Ia** and water (85 °C, 1 h, under helium), **5IIb** was found to decompose only ca. 1.2 times faster than **5Ib**.

(52) Such a behavior is exhibited by coordinating solvents with hydroperoxides, see: Sheldon, R. A.; Van Doorn, J. A.; Schram, C. W. A.; De Jong, A. J. *J. Catal.* **1973**, *31*, 438.

(53) Sander, E. G.; Jencks, W. P. *J. Am. Chem. Soc.* **1968**, *90*, 6154.

(54) (a) Durham, L. J.; Wurster, C. F.; Mosher, H. S. *J. Am. Chem. Soc.* **1958**, 80, 332. (b) Durham, L. J.; Mosher, H. S. *J. Am. Chem. Soc.* **1960**, *82*, 4537.

Table 2. Trend of the Ia-Catalyzed Hydrolysis of 1,2-Epoxyoctane (2a) and -decane (2b) under Two-Phase Conditions (without Added Solvent) in the Presence of Hydrogen Peroxide of Different Concentration[a]

run	epoxide	% H_2O_2 w/v	procedure	% conv **2** to **3**[b,c] 70 °C	% conv **2** to **3**[b,c] 85 °C	% unconv **2**[b] 70 °C	% unconv **2**[b] 85 °C
1	**2a**	16	A	13.5 (8.5)		77	
2	**2a**	40	A	35 (44)		11	
3	**2b**	16	A		4.2 (6.7)		88.5
4	**2b**	40	A		22 (47)		18
5	**2a**	16	B	6.3 (0.8)		92	
6	**2a**	40	B	15 (7)		77	
7	**2b**	16	B		0.8 (tr)		99
8	**2b**	40	B		4.2 (1.5)		94
9	**2b**[d]	40			34.5 (42)		7.5
10	**2b**[e]	40	A		3.8 (14.6)		79

[a] Unless otherwise stated, all experiments were performed on 3 mmol of epoxyalkane by reacting the epoxide under stirring with the **Ia**/H_2O_2 (16% or 40% w/v) biphasic system (procedure A) or with the sole aqueous phase of the latter (procedure B) at the indicated temperature for 30 min, as described in detail in Experimental Section. [b] GC determination (against an internal standard). [c] In procedure A, the indicated value also includes the α-ketol formed by subsequent oxidation of the 1,2-diol under the reaction conditions. The value in parentheses refers to % conversion of the epoxide into the β-hydroperoxy alcohol. The remaining part of the converted epoxide essentially consisted of condensation products. In procedure A, small amounts of the related aldehyde and carboxylic acid of one less carbon were also formed. [d] 1,2-Epoxydecane (3 mmol) was caused to react under stirring with 40% w/v aq H_2O_2 (1.27 mL) in which 10 mg (ca. 0.04 mmol) of tungstic acid was previously dissolved. [e] The neutral complex methyltrioctylammonium μ-oxo-bis[oxodiperoxotungstate(VI)][60a] was used as catalyst in place of **Ia**. To equalize the amount of tungsten present in complex **Ia**, 0.06 mmol of the former complex (equivalent to 0.12 mmol of tungsten) was used.

depending on the concentration of the hydrogen peroxide used at first sight may seem surprising in view of the fact that the primary source of the acidity promoting the hydrolytic opening of the oxirane ring is the same: the metal catalyst. However, this puzzling feature is explicable if one keeps in mind that the aqueous phase in the two biphasic reaction systems is different in character.

It has long been known[56] that the pH meter readings in aqueous solutions of hydrogen peroxide are lower than the "real pH" (in water) and the difference, revealed by the glass−calomel electrode system as a shift in the E_0 value, increases with the increasing concentration of hydrogen peroxide. This behavior has been related[56] to the difference in free energy of solvation of the proton in water and in nearly anhydrous hydrogen peroxide (about 9 kcal/mol), which indicates that the proton is more firmly bound to water. Accordingly, a water molecule, by interaction with neighboring hydrogen peroxide molecules, has its basicity reduced, and the extent of this reduction changes with the percentage of hydrogen peroxide in the aqueous medium.[57]

Thus it appears that the experiments using hydrogen peroxide in acidic aqueous solution but differing in the concentration of this reagent differ also in the acidity of the reaction medium, which is invariably higher than when the medium is exclusively aqueous, despite the fact the "real pH" values are the same. Therefore, if a reaction requiring acid catalysis, as is the case for the epoxide hydrolysis, is involved therein, it must feel the effects of this situation, as shown by the following comparative experiments (performed under homogeneous conditions).

Three acidic (H_3PO_4, 0.8 mg) solutions (1.3 mL) of propylene oxide (3 mmol), two in aqueous hydrogen peroxide (37% and 16% w/v, respectively) and the third one in water alone, were kept under stirring for 1 h at 30 °C. In the first experiment, GC analysis revealed the formation of 67% of 1,2-propanediol (in addition to 20% of the 2(1)-hydroperoxy-1(2)-propanol mixture), while 47% of the above diol was formed (along with 4.5% of the corresponding regioisomeric β-hydroperoxy alcohols) when hydrogen peroxide of lower strength was used, the remaining part being substantially unconverted propylene oxide. Finally, in the last experiment the diol formed was only 34%.

Reverting now to the aforementioned two-phase hydrolysis experiments in the presence of hydrogen peroxide and catalyst **Ia** (Table 2, runs 1−4), it appears reasonable that the effects on the acid hydrolysis of epoxyalkanes **2a,b** related to the different concentration of the hydrogen peroxide used are much more pronounced than in a monophasic system (apart from the efficiency of the reaction which, of course, is lower).

In fact, the difference in acidity existing betweeen the two types of experiments (16% and 40% w/v H_2O_2) with regard to the aqueous phase of the **Ia**/H_2O_2 two-phase system (see Experimental Section) could be greater at the interface, where the epoxyalkane hydrolysis presumably occurs, as a consequence of the fact that the "more lipophilic" hydrogen peroxide is expected to pass into the organic phase preferably to water, in proportion to its concentration. On the other hand, depending on its concentration, hydrogen peroxide could also exert some "homogenizing action" on the phases, which favors acid-activation of the epoxide and its interaction with the aqueous medium. The polar features of the products themselves arising from the oxirane opening could contribute to the purpose.

The trend of runs 1−4 of Table 2 is confirmed by the data of separate experiments, reported in the same table (runs 5−8), which correlate the aptitude to hydrolysis of epoxyalkanes **2a,b** with the concentration (16% or 40% w/v) of hydrogen peroxide used when the former are caused to react with the sole aqueous phase of the **Ia**/H_2O_2 biphasic system (procedure B) rather than with the entire system (procedure A).

From the comparison of the data of runs 1−4 and 5−8 of Table 2 it turns out, however, that in the latter case the hydrolysis rate of **2a,b** is much lower. In particular, the acidity of the sole aqueous phase of the **Ia**/H_2O_2 biphasic system appears to be virtually inadequate to promote hydrolysis of more lipophilic long-chain epoxyalkanes such as 1,2-epoxydecane (**2b**) under two-phase conditions, even when more concentrated hydrogen peroxide is used (Table 2, run 8). This leads us to argue that the results of runs 1−4 of Table 2 are attained mainly due to the catalytic contribution of acidic species (arising from the hydrolytic degradation of catalyst **Ia**) which are likely held more effectively in the organic phase by the "onium" group under the oxidizing reaction conditions.[58]

That hydrolysis of **2a,b** occurs mostly by Brönsted rather than Lewis acid catalysis is suggested also by the

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(55) (a) Späth, E.; Pailer, M.; Schmid, M. *Chem. Ber.* **1941**, *74*, 1552. (b) Swern, D. *Organic Peroxides*; Wiley-Interscience: New York, 1970; Vol. 1, Chapter 1, pp 24−26.

(56) Kolczynski, J. R.; Roth, E. M.; Shanley, E. S. *J. Am. Chem. Soc.* **1957**, *79*, 531.

(57) Mitchell, A. G.; Wynne-Jones, W. F. K. *Discuss. Faraday Soc.* **1953**, *15*, 161.

following observations. First, when (paralleling procedure B of Table 2) 1,2-epoxydecane (**2b**) was put into contact under stirring with an aqueous solution of hydrogen peroxide (40% w/v) containing an amount of tungstic acid ca. 5 times greater than that present (along with phosphoric acid) in the aqueous phase of the **Ia**/H_2O_2 biphasic system (for details, see Experimental Section under the heading Acidity of the Aqueous Phase...), the reaction trend was comparable to that observed with the same epoxide adopting procedure A (Table 2, cf. runs 3 and 9).[59] Second, when a tungsten peroxocomplex able to ensure nearly neutral reaction conditions, $[(C_8H_{17})_3NCH_3]_2[(O_2)_2W(O)O(O)W(O_2)_2$ (methyltrioctylammonium μ-oxo-bis[oxodiperoxotungstate(VI)]),[60a] was employed with the epoxide **2b** as a catalyst in place of **Ia** under the same conditions, a much less satisfactory result was obtained (Table 2, cf. runs 3 and 10).

Needless to say, the use of more concentrated hydrogen peroxide for the reasons above stated also favors the perhydrolysis of **2a,b** in addition to the hydrolysis. As emerges from the data of Table 2 (cf. runs 1–4 and 5–8), the presence of peroxocomplex **Ia** as such (procedure A) leads to an increased proportion of the perhydrolysis product compared to that of hydrolysis, other conditions being equal. A similar effect is also observed employing the neutral tungsten peroxocomplex mentioned above (run 10) or tungstic acid (in substantial amount) dissolved in hydrogen peroxide (run 9) as a catalyst. It may well be that the presence of a tungsten peroxidic species (preformed or generated in situ) makes hydrogen peroxide much more accessible than water to interaction with the epoxyalkane. Ascertaining the origin of this effect requires further study, however.

Thus, according to the results of the experiments reported above, the choice we made initially of utilizing, in the present olefin-to-acid oxidation, hydrogen peroxide more concentrated than that usually used by us (16% w/v) in the alkene epoxidation[13] proves itself, a posteriori, a prerequisite for the success of the reaction in the case of medium- and long-chain alkenes. With these substrates, the perhydrolytic and hydrolytic pathways are both favored by the above circumstance, given the fact that the epoxides involved are highly lipophilic and little prone to undergo ring opening by hydrogen peroxide or water (initiating the two pathways) under the heterogeneous reaction conditions.

Conversely, with arylalkenes and C_5–C_7 cycloalkenes, the use of hydrogen peroxide of lower strength would not affect the reaction course appreciably, owing to the hydrolytic/perhydrolytic lability of the respective intermediate epoxides even under two-phase conditions.

B. The Solvent as Hindrance to the Oxirane-Opening Step in a Two-Phase Reaction System. The fact that for medium- and long-chain alkenes, under the heterogeneous conditions adopted, ring opening of the intermediate epoxyalkanes by hydrogen peroxide or water represents the critical point of the reaction explains why the use of the solvent leads, in these cases, to a progressive, marked worsening of the oxidation on passing from a C_8 to a C_{16} alkene.

Under these conditions, the interaction between the epoxyalkane and the nucleophile, already rather difficult in itself as we have seen, is made even more difficult, in right ratio to the increasing lipophilic character of the epoxyalkane involved, with obvious negative effects on the course of the whole oxidation. As confirmed by control experiments carried out with added solvent, the slowing of the reaction is accompanied by a larger nonproductive consumption of hydrogen peroxide per mole of carboxylic acid formed, which ultimately results in a decrease in efficiency and selectivity of the oxidation, depending on the substrate and solvent used.

C. Biphasic (without Added Solvent) versus Monophasic Procedure. For what has been said with regard to the difficulty of the oxirane-opening step in a two-phase system for the substrates mentioned above, one should expect the adoption of a monophasic procedure (*t*-BuOH as the solvent) to be particularly advantageous in these cases.

In fact, on carrying out the oxidation of medium- and long-chain alkenes with **Ia**/H_2O_2 under homogeneous conditions (20 mL of *t*-BuOH per 10 mmol of alkene, 0.01 mmol of catalyst **Ia**, and 44–55 mmol of 40% w/v H_2O_2), the formed intermediate epoxyalkanes were converted into the corresponding β-hydroperoxy alcohols/1,2-diols much faster than under our “special” two-phase conditions (lack of the solvent). However, the advantages offered by the monophasic procedure in this stage of the reaction were found to be by far frustrated by the slowdown of the other stages, due to both the dilution of the reactants and the presence of water. It is known[1c] that in monophasic systems water seriously retards the hydrogen peroxide epoxidation of alkenes, particularly the less reactive terminal ones. This can account for the modest results (33–45% yield after 24 h) reported,[7,8] for example, for the tungsten-promoted oxidation of 1-octene to octanoic acid with aqueous hydrogen peroxide under homogeneous conditions.

It follows that the special two-phase procedure here described for the oxidation of alkenes to carboxylic acids has to be regarded as a compromise solution ensuring in general the best overall execution of all stages of the reaction.

V. The Role of Catalyst Ia in the Reaction. From this investigation it is apparent that complex **Ia** plays a manifold role in the reaction as a catalyst. First, it exerts (in conjunction with hydrogen peroxide) an oxidizing action toward alkenes,[11–13] transferring its active oxygen to the double bond of these substrates. Which of the structurally different peroxo groups (terminal or bridging)[12] of **Ia** are involved in the oxygen transfer has been estimated so far by theoretical studies on model complexes.[61] These studies suggest that the bridging peroxo group is primary involved in the olefin epoxidation, with the “most electrophilic” oxygen atom adjacent to the triply shared oxygen presumably being transferred to the alkene. Likewise, complex **Ia** acts as oxidant of the 1,2-diol, β-hydroperoxy alcohol, and aldehyde[17] intermediates to give the corresponding α-ketols, α-hydroperoxy ketones, and final carboxylic acids, respectively.

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[58] In the absence of hydrogen peroxide, no appreciable contribution to the hydrolysis of epoxyalkanes **2a,b** by such species was observed.

[59] In contrast, poor results were obtained using 70% $HClO_4$, 96% H_2SO_4, or 85% H_3PO_4 as acid catalysts in place of H_2WO_4 (the first one in the same molar amount, the other two in a molar amount 5-fold greater), under identical conditions. This points to the importance of the lipophilic character of the used acid catalyst for a satisfactory oxirane opening under two-phase reaction conditions.

[60] (a) Prepared according to the procedure described in the literature for the analogous phosphonium complex.[60b] (b) Prandi, J.; Kagan, H. B,; Mimoun, H. *Tetrahedron Lett.* **1986**, *27*, 2617.

[61] Fantucci, P.; Lolli, S.; Venturello, C. *J. Catal.* **1997**, *169*, 228.

The role of **Ia** as a catalyst is not limited to oxidation, however. Being subject to hydrolysis, it can also act as an acid, favoring the "normal" opening of the formed epoxides by hydrogen peroxide or water as well as the "anomalous" rearrangements[40] of medium-sized ring cycloalkene oxides (leading, for example, to formation of diketones or ketodiacids), which characterize the oxidation of the parent cycloalkenes. Acting as an acid, **Ia** also favors the oxidative cleavage of the intermediate α-ketols by hydrogen peroxide. Finally, according to the behavior of transition-metal compounds which form one-electron redox systems,[43] **Ia** can initiate the homolytic decomposition of hydroperoxides such as the β-hydroperoxy alcohol and α-hydroperoxy ketone intermediates.

Conclusion

An efficient procedure has been described for the oxidation of alkenes to carboxylic acids with 40% w/v hydrogen peroxide catalyzed by tungsten peroxocomplex **Ia** under two-phase conditions in the absence of organic solvents. The investigation of the reaction has established that the oxidation proceeds via epoxidation of alkene **1** followed by acid hydrolysis or perhydrolysis of the formed epoxide **2** to give a 1,2-diol **3** and a β-hydroperoxy alcohol **5**, respectively. Metal-catalyzed hydrogen peroxide oxidation of **3** to α-ketol **4** or of **5** to α-oxo hydroperoxide **6** followed, in the former case (hydrolytic pathway), by oxidative cleavage (acid-catalyzed) of **4** and, in the latter (perhydrolytic pathway), by thermal/metal-induced decomposition of **6**, leading to the final carboxylic acid(s) **8**. In the course of the perhydrolytic process, as an alternative to the oxidation of **5** to **8** via **6** (way *a′*), compounds **5** can decompose to carbonyl derivatives **7** or to the corresponding diols (and α-ketols, if the hydroperoxy group is secondary), which also are oxidized to acids **8** (way *a″*). The relative contribution of ways *a′* and *a″* (denoted as the oxidation and decomposition ways, respectively) largely depends on the oxidizability of the hydroxy group (primary or secondary) present in **5** and also on the reaction medium, with hydrogen peroxide exerting a stabilizing action on the β-hydroperoxy alcohol and significantly retarding its decomposition by the metal catalyst.

The perhydrolytic reaction pathway has been found to play a primary role in the oxidation of medium- and long-chain alkenes to acids, while it intervenes to a rather limited extent in the oxidation of arylalkenes and C_5–C_7 cycloalkenes, for which the hydrolytic reaction pathway is predominant. Evidence for the occurrence of the perhydrolytic pathway and related ways *a′* and *a″* has been acquired by the isolation or detection of the relevant intermediates (β-hydroperoxy alcohols, α-hydroperoxy ketones, aldehydes, etc.) involved.

The study of the reaction has evidenced different roles played by catalyst **Ia** at various stages of the process. Likewise, it has also shown that hydrogen peroxide, in addition to acting in the reaction as an oxidant (in combination with catalyst **Ia**) and a nucleophile, exerts a third important function as a solvent. In this role, depending on its concentration, hydrogen peroxide influences the medium acidity to a different extent and indirectly conditions the efficiency of the hydrolytic reaction pathway (and also of the perhydrolytic one), markedly in the case of medium- and long-chain alkenes, whose epoxides undergo acid ring opening by water or hydrogen peroxide with difficulty under the heterogeneous reaction conditions.

In connection with this observation, a rationale has been provided for the negative effect of the solvent observed in the oxidation of the above substrates to acids. Finally, a comparison of the effectiveness of the present biphasic procedure (without added solvent) and that of an analogous monophasic procedure has shown the superiority of the former.

Experimental Section

Infrared spectra were recorded with a FT-IR spectrometer. ^1H and ^{13}C NMR spectra were obtained at 300 and 75.5 MHz, respectively, using $(CH_3)_4Si$ as an internal standard. Mass spectra were obtained at 70 eV on a triple quadrupole mass spectrometer coupled to a gas chromatograph. The columns used were the same as for the GC analyses (see below). Unless otherwise stated, CI mass spectra were recorded using isobutane as the reactant gas. GC analyses were performed on a flame ionization gas chromatograph (with column-temperature programming) using three different bonded-phase, fused silica capillary columns: (a) SPB-5 (30 m × 0.32 mm i.d., 0.25-μm film, Supelco), (b) TAP (5 m × 0.25 mm i.d., 0.10-μm film, Chrompack, for detection of β,β'-dihydroxyalkyl peroxides and ethers as well as of β-hydroperoxy alcohol–aldehyde adducts), and (c) methyl phenyl cyanopropyl silicone (30 m × 0.53 mm i.d., 3.0-μm film, Quadrex, for acetic acid determination). Thin-layer chromatography (TLC) was performed on Merck precoated silica gel 60 F-254 plates, and spots were detected by exposure to iodine fumes or by spraying with a bromophenol blue or potassium permanganate solution, according to the product. Column chromatography was carried out using Merck Kieselgel 60 (70–230 mesh). HPLC analyses were performed using an instrument equipped with a UV detector (at 260 nm). A 10-μL volume of a CH_3CN solution of the sample was injected on an Li Chrospher 100RP-18 end-capped column (Merck, 4 × 250 mm, 5 μm) using a mobile phase of CH_3CN/water with a linear gradient (% CH_3CN from 2 to 100 in 25 min) and a flow rate of 0.8 mL/min. LC/TSP–MS analyses were performed on the same liquid chromatograph interfaced to a triple quadrupole mass spectrometer equipped with a thermospray interface, proceeeding as above. Postcolumn addition of 0.6 mL/min of 0.1 M ammonium acetate in water was performed with a Waters 510 pump.

Products were identified by combustion analysis and spectral data (when isolated) or by gas chromatography–mass spectroscopy (GC–MS) (if necessary, after methylation with CH_2N_2 or silylation with *N*,*O*-bis(trimethylsilyl)acetamide (BSA)/pyridine or -trifluoroacetamide (BSTFA)/pyridine (1:1)) in comparison with authentic samples and/or the literature values. Except for 2-hydroperoxy-2-phenylethanol **5If**,[26] all of the isolated β-hydroperoxy alcohols (as either a single component or a regioisomeric mixture) have not been described before. They were usually stored in the freezer (−25 °C) for some weeks without appreciable decomposition. Also α-hydroperoxy ketones **6IIb** (detected in the reaction mixture) and **6d** (isolated) have so far not been reported.

Silylation (BSTFA) of compounds **5a**–**f** and **6d** was performed at room temperature. For compounds **5c,d**, it usually required about 24 h to be complete. In the case of **5If** and **6d**, if silylation was performed on the isolated product, pyridine was omitted and diethyl ether was used as the solvent. When obtained from the isolated product, the silyl derivative of 6-hydroperoxy-5-decanone (**6d**) was relatively stable (90% unchanged after 24 h). However, if formed in situ in the reaction mixture (in the presence of the catalyst), it gradually transformed through the formation of 5,6-decanedione[62a] into the enol trimethylsilyl (TMS) ether derivative of the latter (*E*/*Z* mixture; configuration not assigned) according to the known[62b] mode of reaction of the silylating agents with compounds containing an enolizable ketone group. 5-Trimethylsiloxy-4-decen-6-one, $C_4H_9COC(OSiMe_3)=CHC_3H_7$: GC–MS *m*/*z* (rel intensity) (EI) 242 (5, M$^+$), 227 (77), 183 (34), 157 (9, [M − C_4H_9CO]$^+$), 143 (10), 75 (45), 73 (100). The above transformation was greatly accelerated by the presence of pyridine.

The evaluation of the aldehyde(s) present in the reaction mixture by GC analysis required prior reduction of the hydroperoxide compounds with triphenylphosphine.

Materials. Catalyst complex methyltrioctylammonium tetrakis(oxodiperoxotungsto)phosphate (**Ia**) was prepared according to the reported procedure.[13] All olefins used in this work were commercial products (Fluka, Aldrich, or Ega-Chemie) and were purified by distillation before use. Hydrogen peroxide (40% w/v aqueous solution, Fluka) was used as such or after appropriate dilution. Noncommercial epoxides tested in this work were made by the standard method from the corresponding olefins and *m*-CPBA. Specimens for the comparison of noncommercial *vic*-diols[63] and α-ketols[64] involved in this work as well as of δ-acetoxypentanoic acid,[65] 4-oxooctanedioic acid,[66] 4-hydroxyoctanedioic acid γ-lactone,[66] and 1,4-cyclooctanedione[67] were prepared according to literature procedures. Specimens of 1-hydroperoxy-2-octanol (**5IIa**) and -decanol (**5IIb**) free of the respective regioisomer **I** were prepared from the corresponding epoxides and alkaline hydrogen peroxide adapting the procedure described in the literature[26] for analogous 1-hydroperoxy-2-hydroxy derivatives. The epoxide (**2a** or **2b**, 30 mmol), dissolved in a solution (230 mL) of methanol/water (11:1) containing 7 g of 85% KOH, was allowed to react under stirring for 7 h at 30 °C with 40% w/v aqueous hydrogen peroxide (80 mL). At the end, the solution was poured into water (1200 mL), salted out with $(NH_4)_2SO_4$ (30 g), and extracted with Et_2O (4 × 100 mL). The combined ether extracts were dried (Na_2SO_4), filtered, and evaporated, and the residue was chromatographed over silica gel (CH_2Cl_2/EtOAc 7:3). From the product thus isolated (62−63% yield), containing ca. 5% of the undesired regioisomer, a pure sample of **5IIa** (as a viscous oil) or **5IIb** (as a white solid, mp 33−34 °C, from Et_2O/*n*-hexane at −25 °C) could be obtained after further elutions (acetone/*n*-hexane 3:7).

Oxidative Cleavage of Olefins to Carboxylic Acids. General Procedure. A three-necked round-bottom flask equipped with a Teflon-coated magnetic bar stirrer, thermometer, reflux condenser, and dropping funnel was charged with methyltrioctylammonium tetrakis(oxodiperoxotungsto)phosphate (**Ia**)[68] (0.5 or 0.6 mmol, see Table 1) and the appropriate olefin (50 mmol). The vigorously stirred mixture was warmed to 60−70 °C (30−40 °C in entry 9), and then a 40% w/v aqueous hydrogen peroxide solution [150, 200, or 250 mmol depending on the substrate,[19] with (except in entry 15) an additional 10% to 37.5% molar excess (see Table 1)] was dropped into the reaction mixture cautiously, at such a rate as to keep the temperature below 80 °C. After the initial exothermicity had subsided, the hydrogen peroxide addition could proceed quickly and was usually over within 15−20 min. The resulting two-phase mixture was then heated to 85 °C for the appropriate time (see Table 1). At the end, after being allowed to cool to rt (except for entries 10 and 15, where the temperature was kept around 70 °C), the mixture was worked up as follows.

Entries 1−4, 7, and 11−14. Dichloromethane (Et_2O, in entry 2) (20 mL) was added, and the two-phase mixture was stirred for a few minutes, poured into a separatory funnel (the organic layer only, in entry 4), and extracted with 10% Na_2CO_3 (4 × 15 mL). After being washed with Et_2O (10 mL), the basic extracts were acidified with dilute HCl (pH ≈ 1) under stirring, treated with Na_2SO_3 to decompose the unreacted hydrogen peroxide (the pH was adjusted to its original value with some HCl, if necessary), salted out (NaCl) in entries 7 and 12−14, and re-extracted with *n*-pentane (Et_2O in entries 3 and 12−14; CH_2Cl_2 in entry 11) [4 × 30 mL (6 × 50 mL in entry 11)]. The combined organic extracts, washed with water (3 × 7 mL) in entry 4 to remove acetic acid thoroughly, were dried over Na_2SO_4, filtered, and (except in entries 12−14) evaporated to give the desired acid. The product so obtained was either purified by distillation under reduced pressure (entries 1 and 2) or, after dissolution in Et_2O (20 mL), passed through a short column (2.5-cm diameter) of silica gel (30 g) and then eluted with more Et_2O (500 mL) (entry 11). In entry 12, the combined organic extracts were mixed with 12 g of silica gel and the resulting slurry was further dried on a rotary evaporator to yield a powder, which was poured onto the top of a chromatographic column (4.5-cm diameter) filled with silica gel (200 g). $CHCl_3$/acetic acid (9:1) was then passed through the column, and the fraction R_f 0.64 was collected. After removal of the solvent under water pump vacuum, *n*-pentane (50 mL) was added to the isolated solid product repeatedly, and the solvent was evaporated after each addition to remove acetic acid thoroughly. Finally, the product was dried under reduced pressure. In entries 13 and 14, the combined organic extracts were analyzed directly by GC after silylation (BSTFA) at 60 °C using *n*-eicosane and *n*-tetracosane, respectively, as the internal standard.

Entries 5 and 8. Diethyl ether (80 mL) was added under stirring (in entry 8, the solid formed was dissolved). After the unreacted hydrogen peroxide was decomposed as above, the organic layer was separated and the aqueous one was salted out (NaCl) and extracted with Et_2O (3 × 80 mL). The ether extracts were combined with the original organic layer, dried (Na_2SO_4), and analyzed by GC after silylation (BSA) at 60 °C using *n*-dodecane as the internal standard.

Entry 6. 1,2-Dichloroethane (DCE, 80 mL) was added under stirring to dissolve the solid formed. The resulting two-phase mixture was poured into a separatory funnel, more DCE (120 mL) was added, and the organic layer was separated. Into this phase a 10% Na_2CO_3 solution (60 mL) was dropped quickly with stirring to precipitate the sodium salt, which was separated, made thoroughly solvent-free, and dissolved in hot water (600 mL). The aqueous solution was stirred, acidified with dilute HCl, cooled, and extracted with *n*-pentane (4 × 80 mL), and the extract was then worked up as in entries 1 and 2.

Entry 9. Dichloromethane (20 mL) was added under stirring, and the aqueous layer was separated, washed with CH_2Cl_2 (2 × 5 mL), treated with concentrated HCl (ca. 1 mL) and then Na_2SO_3 (1 g) to decompose the unreacted hydrogen peroxide, salted out with $(NH_4)_2SO_4$ (17 g), and extracted with Et_2O (4 × 50 mL). The combined and dried (Na_2SO_4) ether extracts were concentrated to 50 mL, passed through a short column of silica gel as in entry 11, and then eluted with more Et_2O (250 mL). On evaporation of the solvent, the desired acid was obtained as a white solid.

Entries 10 and 15. 1,2-Dichloroethane (1 × 20 mL, 2 × 5 mL) was added, and after each addition, the two-phase mixture was stirred for a few minutes and then the lower organic layer was siphoned off.[69] The aqueous layer was stored in a refrigerator (5 °C) overnight to afford a crystalline precipitate, which was filtered, washed with CH_2Cl_2 (3 × 5 mL), and dried.

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(62) (a) Nonsilylated secondary α-hydroperoxy ketones are known to easily form α-diketones by dehydration, see: Bayley, E. J.; Barton, D. H. R.; Elks, J.; Templeton, J. F. *J. Chem. Soc.* **1962**, 1578 and references therein. (b) Poole, C. F. In *Handbook of Derivatives for Chromatography*; Blau, K., King, G. S., Eds.; Heyden & Son Ltd.: London, 1978; Chapter 4, pp 160−165.

(63) (a) Swern, D.; Billen, G. N.; Findley, T. W.; Scanlan, J. T. *J. Am. Chem. Soc.* **1945**, *67*, 1786. (b) Fieser, M.; Fieser, L. F. *Reagents for Organic Synthesis*; Wiley: New York, 1967; Vol. 1, p 796.

(64) (a) Tsuji, T. *Tetrahedron Lett.* **1966**, *22*, 2413. (b) Srinivasan, N. S.; Lee, D. G. *Synthesis* **1979**, 520. (c) Sakata, Y.; Ishii, Y. *J. Org. Chem.* **1991**, *56*, 6233.

(65) Andreev, V. M.; Polyakova, S. G.; Bazhulina, V. I.; Khrustova, Z. S.; Smirnova, V. V. *J. Org. Chem. USSR (Engl. Transl.)* **1981**, *17*, 79.

(66) Holmquist, H. E.; Marsh, F. D.; Sauer, J. C.; Engelhardt, V. A. *J. Am. Chem. Soc.* **1959**, *81*, 3681.

(67) Cope, A. C.; Fenton, S. W.; Spencer, C. F. *J. Am. Chem. Soc.* **1952**, *74*, 5884.

(68) Due to its syrupy nature, complex **Ia** was preferably employed as a dichloromethane solution of known concentration, with the solvent subsequently removed.

(69) In entry 10, small amounts (ca. 0.2 g) of product separated from the siphoned organic layer by standing. They were collected, washed with CH_2Cl_2, and combined with the crystals precipitated from the aqueous layer.

In a method similar to that for the aqueous layer in entry 9, the mother liquor was extracted with Et_2O (4 × 30 mL). On evaporation of the dried (Na_2SO_4) ether extracts, a solid (pasty, in entry 15) residue was obtained, which was washed with CH_2Cl_2 (3 × 3 mL) to give a second crop (0.3−0.4 g) of the desired acid as a white powder. In entry 15, the major and minor crop of the product so obtained were combined and dissolved in boiling CH_3CN (20 mL), from which the pure acid recrystallyzed on standing at −25 °C.

6-Oxoheptanoic Acid: low-melting solid, mp 32−33 °C (Et_2O/*n*-pentane at −25 °C) [lit.[70] mp 33−34 °C]; ^1H and ^{13}C NMR spectra[7] and the mass spectrum (as methyl ester)[71] were in accord with published data.

5-Oxodecanedioic Acid: mp 115−116 °C (DCE) [lit.[72] mp 115−116 °C]; GC−MS (as dimethyl ester) *m/z* (rel intensity) (EI) 244 (1, M^+), 213 (3), 181 (18), 143 (20, $[CO(CH_2)_4COOCH_3]^+$), 129 (28, $[CO(CH_2)_3COOCH_3]^+$), 111 (48), 101 (40), 59 (79), 55 (100), 41 (44); ^1H and ^{13}C NMR spectra were in accord with published data.[73]

Interrupted Oxidation of Epoxides (or their Parent Alkenes) with Ia/H_2O_2 (40% w/v). Formation of *β*-Hydroperoxy Alcohols. The reaction is illustrated by the following examples referred to the examined model epoxides **2a**−**f**. Into a stirred mixture of catalyst **Ia** (0.226 g, 0.1 mmol) and 1,2-epoxyoctane (**2a**) (97% pure; 1.321 g, 10 mmol), warmed to 60−70 °C, was dropped 40% w/v aqueous hydrogen peroxide (4.25 mL, 50 mmol)[74] over a period of 5−6 min, with care taken to control the initial exothermicity. The resulting two-phase mixture was then heated at 85 °C for 30 min (almost quantitative conversion of the epoxide, ca. 20% conversion of H_2O_2). After the mixture cooled, Et_2O (15 mL) was added with stirring, the organic layer was separated, and the aqueous layer was salted out with $(NH_4)_2SO_4$ (2(3 g) and then extracted with Et_2O (2 × 15 mL). The combined, dried (Na_2SO_4), and filtered organic layers were analyzed, after silylation (BSTFA), by GC using *n*-tetradecane as an internal standard.

The same procedure was followed with 1,2-epoxydecane (**2b**), *trans*-4,5- and -5,6-epoxydecane (**2c** and **2d**), and cyclohexene and styrene oxides (**2e** and **2f**), except that with the last two compounds water (1 mL) was added initially to the epoxide/catalyst **Ia** mixture in order to achieve better thermal control during hydrogen peroxide addition (cf. also footnote *d* of Table 1) and the reaction time was shortened to 10 min, while it was prolonged to 1 h with epoxides *trans*-**2c,d**. When the reaction was stopped, epoxide conversion was 92−93% for **2b**, less than 30% for *trans*-**2c,d**, and almost quantitative for **2e,f**, and H_2O_2 conversion was 17−18% for **2b** and 8−9% for **2c**−**f**.

β-Hydroperoxy alcohol intermediates **5a**−**f** were formed along with the corresponding *vic*-diols/α-ketols and small or moderate amounts of the final acids and related aldehydes (for the pertinent data, cf. text). Compounds **5a**−**c** were obtained as a regioisomeric mixture. Where the two regioisomers (silylated) could be revealed by GC as distinct peaks (**5a,b**), regioisomer **I** was found to elute first.

Interrupted-oxidation experiments with the parent alkenes **1a**−**f** (in place of epoxides **2a**−**f**) were carried out under identical conditions. When the reaction was stopped, alkene conversion ranged from 90% with **1a,f** to 96% with **1b** and to 98−99% with **1c**−**e**, whereas the unreacted (on converted olefin) intermediate epoxide was around 1% for **2a**, 48% for **2b**, 78−80% for **2c,d**, and absent for **2e,f**.

Isolation of *β*-hydroperoxy alcohols **5a**−**f** (formed from epoxides) was accomplished on the organic extracts resulting from workup[75] of the reaction as described below. However, in the case of compounds **5c**−**f**, for which an adequate accumulation of product (to be isolated) was not possible with the interrupted-oxidation procedure reported above (paralleling the actual reaction conditions), a somewhat modified oxidation procedure (cf. also the text) was used to obtain the desired compounds to a more satisfactory extent. It implied (a) with epoxides *trans*-**2c,d** the use of 70% w/w H_2O_2 (in a 2:1 molar ratio to the epoxide), directly charged in the reactor, at 60 °C (reaction time, 75 min; 97−99% conversion of the epoxide; 55−58% conversion of H_2O_2) and (b) with epoxides **2e,f** the dropwise addition of 40% w/v H_2O_2 (in a 5:1 molar ratio to the epoxide) over 5−6 min into the epoxide/catalyst **Ia**/water mixture (cooled with an ice/water bath), which was then kept under stirring for 30 min at room temperature (96−97% conversion of the epoxide; 5−6% conversion of H_2O_2).

To isolate **5a**−**f**, the above-mentioned organic extracts were concentrated under reduced pressure and the residue was chromatographed on SiO_2 (50 g, ethyl acetate/CH_2Cl_2 as an eluent). The fraction of appropriate R_f was collected and further purified on SiO_2, eluting with acetone (Et_2O)/*n*-hexane (for details, see the individual compounds). Careful rotoevaporation (30−40 °C) of the solvent, at first under slightly reduced pressure and then at 1−2 mmHg (to remove the last traces of solvents and moisture), gave the desired product, 95−97% pure by GC. In the case of compounds **5a,b**, prior to the second elution the crude product obtained was dissolved into Et_2O (15 mL) and stirred with a solution of Na_2CO_3 (80−120 mg) in a minimum of water at rt for 15−20 min to remove residual contamination by organic acids as evidenced by GC. Yields; chromatography eluents; and R_f, spectral, physical, and analytical data of the isolated products **5a**−**f** are as follows.

2(1)-Hydroperoxy-1(2)-octanols (5a) were isolated as a colorless oil in 35% yield (ethyl acetate/CH_2Cl_2 3:7 and then acetone/*n*-hexane 3:7 as eluents; R_f 0.47 and 0.38). The two regioisomers **5Ia** and **5IIa** (ratio ca. 2.7:1)[76] could not be separated. Their NMR data were assigned from the mixture. The signals for **5IIa** were confirmed on the pure compound obtained by an independent synthesis (see above).

5Ia: ^1H NMR (DMSO-d_6) δ 0.86 (t, 3 H), 1.05−1.75 (m, 10 H), 3.46 (ddd after OH proton decoupling, J = 11.4, 5.0, 4.7 Hz, 2 H, CH_2OH), 3.58−3.82 (m, 1 H, CHOOH), 4.48 (t, J = 5.7 Hz, 1 H, CH_2OH), 11.21 (s, 1 H, CHOOH) ppm; ^{13}C NMR ($CDCl_3$) δ 14.08, 22.65, 25.68, 28.72, 29.37, 31.77, 62.95, 85.86 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI) 307 (100, MH^+), (EI) M^+ absent, 201 (7), 187 (28), 147 (100, $[Me_2Si{=}O{-}SiMe_3]^+$), 103 (62, $[CH_2OSiMe_3]^+$), 89 (50), 73 (57, $[SiMe_3]^+$).

5IIa: ^1H NMR (DMSO-d_6) δ 0.86 (t, 3 H), 1.05−1.75 (m, 10 H), 3.58−3.82 (m, 3 H, CH_2OOH + CHOH), 4.55 (d, J = 5.0 Hz, 1 H, CHOH), 11.58 (s, 1 H, CH_2OOH) ppm; ^{13}C NMR ($CDCl_3$) δ 14.08, 22.65, 25.46, 29.37, 31.79, 32.96, 69.60, 80.79 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI) 307 (100, MH^+), (EI) M^+ absent, 261 (6), 187 (100, $[C_6H_{13}CHOSiMe_3]^+$), 147 (83), 73 (34).

5a: IR (neat) ν_{max} 3321, 1075 (sh), 1052, 1039, 816 cm^{-1}.

2(1)-Hydroperoxy-1(2)-decanols (5b) were isolated as a colorless oil in 45% yield (ethyl acetate/CH_2Cl_2 3:7 and then acetone/*n*-hexane 3:7 as eluents; R_f 0.53 and 0.48). The two regioisomers **5Ib** and **5IIb** (ratio ca. 2:1)[76] could not be separated. Their NMR data were assigned from the mixture. The signals for **5IIb** were confirmed on the pure compound obtained by an independent synthesis (see above).

5Ib: ^1H NMR (DMSO-d_6) as for **5Ia** except the signal at δ 1.05−1.75 ppm corresponds to 14 H; ^{13}C NMR ($CDCl_3$) δ 14.11, 22.72, 25.74, 28.73, 29.35, 29.56, 29.75, 31.94, 62.92, 85.83 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI) 335 (100, MH^+), (EI) M^+ absent, 229 (3), 215 (22), 147 (100), 103 (40), 89 (27), 73 (32).

5IIb: ^1H NMR (DMSO-d_6) as for **5IIa** except the signal at δ 1.05−1.75 ppm corresponds to 14 H; ^{13}C NMR ($CDCl_3$) δ

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(70) Acheson, R. M. *J. Chem. Soc.* **1956**, 4232.

(71) Thoma, H.; Spiteller, G. *Liebigs Ann. Chem.* **1983**, 1237.

(72) Leonard, N. J.; Goode, W. E. *J. Am. Chem. Soc.* **1950**, *72*, 5404.

(73) Osowska-Pacewicka, K.; Alper, H. *J. Org. Chem.* **1988**, *53*, 808.

(74) The high H_2O_2:substrate molar ratio (5:1) used in these experiments was chosen to simulate the reaction conditions (volume ratio of the organic versus aqueous phase) as close as possible.

(75) While preferred as a solvent for analytical purposes, Et_2O was replaced with CH_2Cl_2 to achieve the isolation of compounds **5a**−**f**. This change made it possible to minimize the extraction of hydrogen peroxide into the organic phase, which was found to complicate the separation. Furthermore, except for **5e**, salting out of the aqueous layer with $(NH_4)_2SO_4$ prior to extraction with CH_2Cl_2 was omitted.

(76) Determined by GC (after silylation) and NMR.

14.11, 22.72, 25.52, 29.35, 29.56, 29.75, 31.94, 32.97, 69.55, 80.78 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI) 335 (100, MH$^+$), (EI) M$^+$ absent, 289 (6), 215 (100, [C$_8$H$_{17}$CHOSiMe$_3$]$^+$), 191 (27), 147 (82), 73 (27).

(4*RS*,5*SR*)-5(4)-Hydroperoxy-4(5)-decanols (5c) were isolated as a colorless oil in 63% yield (ethyl acetate/CH$_2$Cl$_2$ 1:4 and then acetone/*n*-hexane 3:7 as eluents; R_f 0.57 and 0.53). The two regioisomers **5Ic** and **5IIc** (ratio 1:1)[77] could not be separated. ^{1}H NMR (DMSO-d_6) δ 0.70−1.02 (m, 6 H), 1.10−1.65 (m, 12 H), 3.42−3.56 (m, 1 H, C*H*OOH), 3.56−3.76 (m, 1 H, C*H*OH), 4.313 and 4.319 (d, J = 5.8 Hz, CHO*H*) (1 H), 11.115 and 11.120 (s, CHOO*H*) (1 H) ppm; ^{13}C NMR (CDCl$_3$) δ 14.04, 14.08, 14.10, 19.47, 19.58, 22.56, 22.62, 25.97, 26.09, 26.50, 28.58, 31.72, 31.92, 33.84, 71.68, 71.96, 88.05, 88.39 ppm; GC−MS (as bis(TMS) derivative) **5Ic**, *m/z* (rel intensity) (CI) 335 (100, MH$^+$) (EI) M$^+$ absent, 147 (85), 145 (95, [C$_3$H$_7$CHOSiMe$_3$]$^+$), 73 (100), **5IIc**, *m/z* (CI) 335 (100, MH$^+$) (EI) M$^+$ absent, 173 (78, [C$_5$H$_{11}$CHOSiMe$_3$]$^+$), 147 (82), 73 (100). The configuration of **5c** was established as follows. A sample of **5c** (96% pure; 0.198 g, 1 mmol) in Et$_2$O (10 mL) was stirred for 15 min at rt with a solution of (C$_6$H$_5$)$_3$P (0.341 g, 1.3 mmol) in Et$_2$O (15 mL). Elution on an SiO$_2$ column (15 g, Et$_2$O as an eluent, R_f 0.78) gave a 90% yield of *erythro*-4,5-decanediol, mp 115−117 °C (MeCN) [lit.[33b] mp 118−118.5 °C].

***erythro*-6-Hydroperoxy-5-decanol (5d)** was isolated as a colorless oil[78] in 61% yield (ethyl acetate/CH$_2$Cl$_2$ 1:4 and then acetone/*n*-hexane 3:7 as eluents; R_f 0.59 and 0.57): ^{1}H NMR (DMSO-d_6) δ 0.87 (two overlapping t, 6 H), 1.10−1.80 (m, 12 H), 3.48 (five-line m, 1 H), 3.55−3.70 (m, simplifies after OH proton decoupling, 1 H), 4.32 (d, J = 5.9 Hz, 1 H), 11.11 (s, 1 H) ppm; ^{13}C NMR (CDCl$_3$) δ 13.93, 14.00, 22.75, 26.18, 28.46, 28.55, 31.41, 71.91, 88.33 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI) 335 (100, MH$^+$) (EI) M$^+$ absent, 159 (100, [C$_4$H$_9$CHOSiMe$_3$]$^+$), 147 (73), 73 (28). Reduction of **5d** with (C$_6$H$_5$)$_3$P and workup as described above for **5c** (Et$_2$O as eluent, R_f 0.80) gave *meso*-5,6-decanediol, mp 134−136 °C (MeCN) [lit.[33b] mp 136−137.5 °C].

***trans*-2-Hydroperoxycyclohexanol (5e)** was isolated as a white solid in 21% yield (ethyl acetate/CH$_2$Cl$_2$ 1:1 and then Et$_2$O/*n*-hexane 4:1 as eluents; R_f 0.53 and 0.46): mp 34−36 °C (Et$_2$O/*n*-pentane at −25 °C); ^{1}H NMR (DMSO-d_6) δ 0.90−1.45 (m, 4 H), 1.45−1.68 (m, 2 H), 1.68−1.85 (m, 1 H), 1.85−2.10 (m, 1 H), 3.32−3.48 (m, simplifies after OH proton decoupling, 1 H), 3.48−3.60 (m, 1 H), 4.66 (d, J = 4.2 Hz, 1 H), 11.25 (s, 1 H) ppm; ^{13}C NMR (CDCl$_3$) δ 23.87, 24.12, 28.49, 32.87, 72.80, 88.50 ppm; GC−MS (as bis(TMS) derivative] *m/z* (rel intensity) (CI) 277 (100, MH$^+$) (EI) M$^+$ absent, 187 (19, [CyOOSiMe$_3$]$^+$), 171 (17, [CyOSiMe$_3$]$^+$), 147 (82), 97 (25), 75 (48), 73 (100). Anal. Calcd for C$_6$H$_{12}$O$_3$: C, 54.53; H, 9.15; (O$_2$)$^{2-}$, 24.22. Found: C, 54.78; H, 9.30; (O$_2$)$^{2-}$, 23.96. Reduction of **5e** with (C$_6$H$_5$)$_3$P and workup as described above for **5c** (Et$_2$O as an eluent, R_f 0.28) gave *trans*-cyclohexanediol, mp 104−105 °C (C$_6$H$_6$) [lit.[79] mp 104.5−105.5 °C].

2-Hydroperoxy-2-phenylethanol (5If) was isolated as a white solid in 22% yield (ethyl acetate/CH$_2$Cl$_2$ 1:1 and then Et$_2$O/*n*-hexane 4:1 as eluents; R_f 0.54 and 0.48): mp 70−71 °C (Et$_2$O/*n*-pentane at −25 °C) [lit.[26] mp 71−73 °C]; ^{1}H NMR (DMSO-d_6) δ 3.56 (ddd after OH proton decoupling, J = 11.9, 7.0, 4.5 Hz, 2 H), 4.83 (dd, J = 7.0, 4.5 Hz, 1 H), 4.91 (t, J = 5.9 Hz, 1 H), 7.27−7.34 (m, 5 H, ArH), 11.61 (s, 1 H) ppm, the ^{1}H NMR data of **5If** previously described[26] were obtained in CDCl$_3$ and not in DMSO-d_6 as here reported; ^{13}C NMR (CDCl$_3$) δ 64.63, 88.43, 127.07, 128.59, 128.63, 137.00 ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (EI) M$^+$ absent,[80] 209 (1), 195 (3, [ArCHOOSiMe$_3$]$^+$), 193 (14, [ArCHCH$_2$OSiMe$_3$]$^+$), 179 (24, [ArCHOSiMe$_3$]$^+$), 147 (100), 133 (16), 119 (4), 103 (29), 73 (81). Anal. Calcd for C$_8$H$_{10}$O$_3$: C, 62.32; H, 6.54; (O$_2$)$^{2-}$, 20.76. Found: C, 61.95; H, 6.50; (O$_2$)$^{2-}$, 20.60.

Reaction of *β*-Hydroperoxy Alcohols (*s*-OH) with Ia/H$_2$O$_2$ at Low Conversion of the Substrate. Formation of Intermediate α-Hydroperoxy Ketones. The procedure is illustrated by the following examples referred to the examined model compounds **5IIb** and **5d**. A stirred mixture of catalyst **Ia** (0.01 mmol) and 1-hydroperoxy-2-decanol (**5IIb**) or *erythro*-6-hydroperoxy-5-decanol (**5d**) (1 mmol) was reacted at 85 °C with 40% w/v hydrogen peroxide (5 mmol).[74] The progress of the reaction was monitored by GC or HPLC (see text, section IIIAa). After 20 min, the maximum yield of the corresponding α-hydroperoxy ketone was observed (78% for **6IIb** and 82% for **6d**, at 17% and 40% conversion of **5IIb** and **5d**, respectively). The amounts of this and the other (minor) intermediates formed (aldehyde, *vic*-diol, and α-ketol, see text) as well as of the final carboxylic acid and unconverted *β*-hydroperoxy alcohol were quantitated by GC as follows. The cooled two-phase reaction mixture was salted out with (NH$_4$)$_2$SO$_4$ (1 g) and shaken with Et$_2$O (3 × 2 mL). To the combined ether extracts was added *n*-tetradecane (for **5IIb**) or *n*-dodecane (for **5d**) as the internal standard. The solution was then diluted to a 10-mL volume with more Et$_2$O and dried (Na$_2$SO$_4$). On an aliquot (1 mL) of this solution, after treatment with BSTFA−pyridine, the products *vic*-diol, α-ketol, and carboxylic acid were determined as their silyl derivatives. Another aliquot was cooled to 4 °C, and an excess of triphenylphosphine was added, whereupon the evaluation of the aldehyde was accomplished. The same aliquot was then treated with BSTFA−pyridine, and the α-hydroperoxy ketone and unconverted *β*-hydroperoxy alcohol were determined as ketol and diol (silylated), respectively. In the case of **6d**, the resulting α-ketol was analyzed in part as the bis(silyl) derivative (enol−TMS−ether−TMS−ether).[62]

1-Hydroperoxy-2-decanone (6IIb), obtained from (**5IIb**) as indicated above, was identified in the reaction mixture by its GC−mass spectrum: *m/z* (rel intensity) (CI) 189 (75, MH$^+$), 171 (100, [MH − H$_2$O]$^+$) (EI) M$^+$ absent, 143 (18), 142 (6), 141 (5), 125 (7), 83 (42), 75 (11, [COCH$_2$OOH]$^+$), 69 (100), 47 (19, [CH$_2$OOH]$^+$), 45 (30). The identity of **6IIb** was confirmed by LC/TSP−MS analysis which showed the presence of a [M + NH$_4$]$^+$ adduct ion at *m/z* 206 in the positive-ion mode and a [M + AcO]$^-$ adduct ion at *m/z* 247 in the negative-ion mode. After treatment of the organic solution containing **6IIb** with (C$_6$H$_5$)$_3$P, the peak corresponding to this compound disappeared in GC or HPLC and a new peak was observed whose GC−mass spectrum was identical to that of an authentic sample of 1-hydroxy-2-decanone. Alternatively, addition of BSTFA−pyridine to the above organic solution led to the formation of a product identified as the 1-trimethylsiloxy-1-*N*-(trimethylsilyl)trifluoroiminoacetoxy-2-decanone adduct C$_8$H$_{17}$COCH(OSiMe$_3$)OC(=NSiMe$_3$)CF$_3$ (see text) by its GC−mass spectrum: *m/z* (rel intensity) (CI) 428 (60, MH$^+$), 356 (30), 338 (100) (EI) M$^+$ absent, 412 (3), 303 (8), 286 (12, [M − C$_8$H$_{17}$CO]$^+$), 168 (20, [CF$_3$C(NSiMe$_3$]$^+$), 147 (10), 102 (40), 73 (100).

In the case of the α-hydroperoxy ketone **6d**, identification was performed on the compound isolated from a scaled-up experiment operating as follows.

6-Hydroperoxy-5-decanone (6d). A stirred mixture of *erythro*-6-hydroperoxy-5-decanol (**5d**) (96% pure, 0.99 g, 5 mmol), catalyst **Ia** (0.113 g, 0.05 mmol), and 40% w/v hydrogen peroxide (2.15 mL, 25 mmol)[74] was heated at 85 °C for 30 min (ca. 13% conversion of H$_2$O$_2$). After the mixture cooled, CH$_2$Cl$_2$ (8 mL) was added with stirring, the organic layer was separated, and the aqueous layer was extracted with CH$_2$Cl$_2$ (2 × 15 mL). The combined, dried (Na$_2$SO$_4$), and filtered organic layers were concentrated under reduced pressure, the residue was chromatographed on SiO$_2$ (Et$_2$O/*n*-hexane 1:1), and the fractions R_f 0.75 and R_f 0.42 were collected. From the latter fraction, 0.615 g of unreacted **5d** (90% pure) was

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(77) Determined by NMR.

(78) 1,1-Dihydroperoxypentane was usually revealed as a contaminant by the ^{1}H NMR spectrum. Its formation was confirmed by an independent preparation from pentanal (**7d**) and hydrogen peroxide: ^{1}H NMR (DMSO-d_6) (selected values) δ 4.98 (t, J = 6.0 Hz, 1 H, C*H*(OOH)$_2$, 11.578 (s, 2 H, OO*H*) ppm; GC−MS (as bis(TMS) derivative) *m/z* (rel intensity) (CI−NH$_3$) 298 (94, [M + NH$_4$]$^+$), 208 (13), 152 (100) (EI) M$^+$ absent, 175 (14, [M − OOSiMe$_3$]$^+$), 147 (6), 119 (100, [CH$_2$OOSiMe$_3$]$^+$), 91 (67, [HOOSiMe$_2$]$^+$), 75 (60), 61 (38).

(79) Rigby, W. *J. Chem. Soc.* **1950**, 1911.

(80) The parent peak could be observed on the mass spectrum of the compound as recorded by direct inlet (DIP-EI): MS *m/z* (rel intensity) 154 (3, M$^+$), 138 (1), 136 (2.5), 123 (52), 121 (65), 106 (63), 105 (100), 77 (58).

recovered (58%). The former fraction was eluted once more with acetone/*n*-hexane 1:9 (R_f 0.24). Careful rotoevaporation of the solvent, at first under slightly reduced pressure and then at 1−2 mmHg (to remove the last traces of solvents and moisture), afforded 0.307 g of 6-hydroperoxy-5-decanone (**6d**) as a colorless oil, 94% pure by GC[81] (75% yield based on consumed **5d**): IR (neat) ν_{max} 3379, 1712 cm^{-1}; ^{1}H NMR (DMSO-d_6) δ 0.80−0.92 (m, 6 H), 1.10−1.40 (m, 4 H), 1.40−1.70 (m, 6 H), 2.61 (ddt, J = 18.1, 7.3 Hz, 2 H), 4.12 (dd, J = 7.4, 6.3 Hz, 1 H), 12.01 (s, 1 H) ppm; ^{13}C NMR (CDCl$_3$) δ 13.76, 13.86, 22.37, 22.46, 25.32, 27.56, 29.18, 37.77, 89.66, 212.26 ppm; GC−MS m/z (rel intensity) (CI) 189 (100, MH$^+$) (EI) M$^+$ absent, 170 (9, [M − H$_2$O]$^+$), 103 (1.5), 99 (1.4), 85 (100, [C$_4$H$_9$-CO]$^+$), 57 (85), 44 (45), 41 (65). As additional chemical structure proof, reduction of **6d** with (C$_6$H$_5$)$_3$P (and relative workup) as described above for **5c** (acetone/*n*-hexane 1:9 as an eluent; R_f 0.40) afforded the expected 6-hydroxy-5-decanone (**4d**) as an oil in 80% yield. IR, ^{1}H NMR, and mass spectra were consistent with published data.[64b]

β-Hydroperoxy Alcohol Decomposition in the Presence of Water and Catalyst Ia (Blank Experiments). In a typical experiment, a stirred mixture of 1-hydroperoxy-2-decanol (**5IIb**) (97% pure, 0.168 g, 1 mmol) and catalyst **Ia** (22.6 mg, 0.01 mmol) was heated for 45 min at 85 °C together with water (425 μL) under an atmosphere of helium. At the end, the reaction mixture was worked up and analyzed by GC as described in the preceding experimentation. The formation of 38% of nonanal (**7b**), 30.5% of 1,2-decanediol (**3b**), and 13% of nonanoic acid (**8b)** was observed, at 34% conversion of **5IIb**. Likewise, the presence (roughly estimated at 7% of converted **5IIb**) of hydroxymethyl 2-hydroxydecyl peroxide (adduct **9**; R^2, R^4 = H, R^3 = n-C$_8$H$_{17}$; see the following heading) and (in a small amount) of 1-hydroxynonyl 2-hydroxydecyl peroxide (adduct **9**; R^2 = H, R^3, R^4 = n-C$_8$H$_{17}$)[82] was ascertained.

In an analogous experiment with *erythro*-6-hydroperoxy-5-decanol (**5d**) (96% pure, 0.198 g, 1 mmol) in place of **5IIb**, after 1 h (at 63% conversion of **5d**) GC analysis revealed the formation of 124% of pentanal (**7d**) (62% referred to decomposed **5d**), 8% of 5,6-decanediol (**3d**), 14% of 6-hydroxy-5-decanone (**4d**), 22% of pentanoic acid (**8d**) (11% referred to decomposed **5d**), and approximately 2% of 1-hydroxypentyl 1-butyl-2-hydroxyhexyl peroxide (adduct **9**; R^2, R^3, R^4 = n-C$_4$H$_9$; see the following paragraph).[83a]

β-Hydroxyperoxyhemiacetals from β-Hydroperoxy Alcohols and Aldehydes. 1-Hydroxypentyl 1-Butyl-2-hydroxyhexyl Peroxide (Adduct 9; R^2, R^3, R^4 = n-C$_4$H$_9$). A mixture of *erythro*-6-hydroperoxy-5-decanol (**5d**) (96% pure, 0.215 g, 1.08 mmol) and freshly distilled pentanal (**7d**) (98% pure, 0.095 g, 1.08 mmol) was stirred under an atmosphere of helium for 10 min at 25 °C. At the end, Et$_2$O was added and the resultant solution was analyzed by GC after silylation (BSTFA), using *n*-dodecane as an internal standard. The presence (along with the unreacted starting compounds) of two major peaks, roughly estimated at 34% on the whole on the basis of charged **5d**, in a 1.6−1.8:1 ratio (attributable to stereoisomers) was observed, whose GC−mass spectra were consistent with the structure of the title adduct: GC−MS (as bis(TMS) derivative) m/z (rel intensity) (CI−NH$_3$) 438 [25, [M + NH$_4$]$^+$), (CI−i-C$_4$H$_{10}$) MH$^+$ absent, 245 (75, [Me$_3$SiOCH-(C$_4$H$_9$)CH(C$_4$H$_9$)O]$^+$), 175 (100, [C$_4$H$_9$CH(OSiMe$_3$)O]$^+$), 159 (53, [C$_4$H$_9$CHOSiMe$_3$]$^+$) (EI) M$^+$ absent, 229 (2.5, [Me$_3$SiOCH-(C$_4$H$_9$)CH(C$_4$H$_9$)]$^+$), 191 (1.5, [C$_4$H$_9$CH(OSiMe$_3$)OO]$^+$), 159 (100), 103 (50), 75 (70), 73 (63). In a duplicate experiment, the stirred mixture of **5d** and **7d** was heated under helium (85 °C, 90 min). Pentanoic acid (**8d**) and 6-hydroxy-5-decanone (**4d**) were formed (molar ratio **8d**:**4d** = 2.8:1),[84] and evolution of H$_2$ was observed. It was checked that, operating under these conditions but in the presence of the sole aldehyde **7d**, the acid **8d** was not formed.

As a proof of the chemical structure of **9** (R^2, R^3, R^4 = C$_4$H$_9$), in another experiment 65% HClO$_4$ (10 μL) was added to the reaction mixture containing the adduct and cyclization in situ of the latter to the corresponding 1,2,4-trioxane derivative was effected (35 °C, 24 h).[85] The formed product was dissolved in Et$_2$O, and the resultant solution was stirred (30 min) with solid NaHCO$_3$ and some droplets of water (to neutralize the acidity present), filtered, and eluted on an SiO$_2$ column (acetone/*n*-hexane 1:9) to afford 0.203 g of 3,5,6-tributyl-1,2,4-trioxane (ca. 94:6 mixture of stereoisomers) as a colorless oil, 96% pure by GC (70% yield): ^{1}H NMR (CDCl$_3$) δ 0.80−1.05 (m, 9 H), 1.16−1.47 (m, 12 H), 1.47−1.66 (m, 6 H), 3.64 (dt, J = 10.6, 3.1 Hz, 1 H), 3.80−4.05 (m, 1 H), 5.195 and 5.34 (t, J = 5.4 Hz) (1 H) ppm, the signal at δ 5.34 ppm integrates to 1:15.3 the area of the signal at δ 5.195 ppm; ^{13}C NMR (DMSO-d_6) δ 13.66, 13.76, 13.89, 21.83, 21.89, 21.95, 24.06, 25.23, 26.87, 27.05, 29.93, 31.40, 76.20, 80.66, 104.05 ppm; GC−MS m/z (rel intensity) (CI) 259 (100, MH$^+$), 173 (19), 157 (37), 139 (24).

Hydroxymethyl 2-Hydroxydecyl Peroxide (Adduct 9; R^2, R^4 = H, R^3 = n-C$_8$H$_{17}$). 1-Hydroperoxy-2-decanol (**5IIb**) (97% pure, 0.168 g, 1 mmol) was stirred for 30 min at 25 °C with 40% w/v formaldehyde (75 μL, 1 mmol) under an atmosphere of helium. At the end, Et$_2$O was added. The resultant solution was dried (Na$_2$SO$_4$), filtered, and analyzed by GC after silylation (BSTFA) using *n*-tetradecane as an internal standard. It showed the presence (along with the starting β-hydroperoxy alcohol) of a major peak, roughly estimated at 39% on charged **5IIb**, whose GC−mass spectrum was consistent with the structure of the title adduct: GC−MS (as bis(TMS) derivative) m/z (rel intensity) (CI) 365 (9, MH$^+$), 247 (86), 245 (56, [C$_8$H$_{17}$CH(OSiMe$_3$)CH$_2$O]$^+$), 229 (100, [C$_8$H$_{17}$CH(OSiMe$_3$)CH$_2$]$^+$), 119 (70, [OCH$_2$OSiMe$_3$]$^+$) (EI) M$^+$ absent, 229 (9), 215 (8), 147 (16), 103 (100, [CH$_2$OSiMe$_3$]$^+$), 75 (76), 73 (61).

If a 10-fold excess of 40% w/v formaldehyde (750 μL) was used (30 °C, 2 h), **5(II)b** could be completely converted, but this essentially led to sizable amounts of the addition product of the title adduct to formaldehyde.

Acidity of the Aqueous Phase of the Ia/H$_2$O$_2$ Biphasic System. In parallel to the reaction conditions, complex **Ia** (0.12 mmol), dissolved in 1,2-dichloroethane (3 mL), was kept in contact under stirring for 15 min at rt with 16% and 40% w/v aqueous hydrogen peroxide (5.1 mL; 24 and 60 mmol, respectively). The resulting aqueous phase was separated and filtered (syringe filter, 25 mm; membrane, cellulose acetate; pore size, 0.45 μm). A pH$_{app}$ of 1.9 and 1.18 (0.1 M solution in KCl), as measured by glass electrode, was observed at rt in the two cases.[86] (If the aqueous hydrogen peroxide was replaced by an equal volume of water alone, the resulting pH

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[81] Purity was determined after converting **6d** into the corresponding α-ketol.

[82] Identified by its GC−mass spectrum: (as bis(TMS) derivative) m/z (rel intensity) (CI) 477 (5, MH$^+$), 245 (85, [C$_8$H$_{17}$CH(OSiMe$_3$)CH$_2$O]$^+$), 231 (100, [C$_8$H$_{17}$CH(OSiMe$_3$)O]$^+$).

[83] (a) The formation of the acid **8d** to a larger extent (22%) as compared to the α-ketol **4d** (14%), which in addition to resulting from the decomposition of **5d** is also coproduced together with **8d** in the thermal decomposition of the formed adduct **9** (R^2, R^3, R^4 = n-C$_4$H$_9$) according to eq 2, leads us to hypothesize a catalytic activity for **4d**. The latter might react with **5d** to give a new adduct which, on decomposition, would afford one molecule of C$_5$ aldehyde and one of the corresponding acid, forming the α-ketol again with the evolution of H$_2$. Ketones are known to react with hydroperoxides to give peroxyhemiketals and peroxyketals.[54a,83b] A similar behavior might also be exhibited by 2-hydroxydecanal **4Ib** (not detected), which is expected to be coproduced in the decomposition of hydroxymethyl and 1-hydroxynonyl 2-hydroxydecyl peroxide adducts (**9**; R^2, R^4 = H, R^3 = n-C$_8$H$_{17}$ and R^2 = H, R^3, R^4 = n-C$_8$H$_{17}$, respectively; cf. eq 2) formed in the blank decomposition of **5IIb** (see Experimental Section). In this case, the reaction of **4Ib** with **5IIb** followed by decomposition of the resultant adduct would give nonanal and formic acid, with the formation of the α-hydroxy aldehyde again and the evolution of H$_2$. (b) Dickey, F. H.; Rust, F.; Vaughan, W. E. *J. Am. Chem. Soc.* **1949**, *71*, 1432.

[84] The value of the ratio decidedly in favor of **8d** parallels the trend observed in the blank decomposition of **5d** (see Experimental Section) and discussed in ref 83a.

[85] For the formation of 1,2,4-trioxanes by the reaction of aldehydes with β-hydroperoxy alcohols in the presence of acids or dehydrating agents, see: (a) Swern, D. *Organic Peroxides*; Wiley-Interscience: New York, 1970; Vol. 3, Chapter 2, pp 108−110. (b) Singh, C. *Tetrahedron Lett.* **1990**, *31*, 69. (c) Refs 28 and 29.

of the aqueous phase was 2.4 under the same conditions.) Ion chromatography analysis of the aqueous phase (after treatment with NaOH) revealed the presence of a quantity of phosphate and tungstate ions amounting to 65−75[87] and 1500−1600 mg/L, respectively. This solution was used in the following experimentation (procedure B).

Ia-Catalyzed Hydrolysis of Epoxyalkanes under Two-Phase Conditions (without Added Solvent) in the Presence of Hydrogen Peroxide of Different Concentration. Pertinent experiments were performed on 1,2-epoxyoctane (**2a**) and -decane (**2b**) following procedures A and B.

Procedure A. The reaction was carried out by keeping under stirring the two-phase mixture made up of the epoxyalkane (3 mmol), catalyst **Ia** (0.03 mmol), and 16% or 40% w/v aqueous hydrogen peroxide (1.27 mL; 6 and 15 mmol, respectively) at 70 °C (**2a**) or 85 °C (**2b**) for 30 min.

Procedure B. An aliquot (1.27 mL) of the acidic aqueous phase of the **Ia**/H_2O_2 (16% or 40% w/v) biphasic system, obtained as described in the preceding heading, was allowed to react under stirring with the epoxyalkane (3 mmol) as in procedure A.

In both procedures, at the end of the reaction Et_2O was added under stirring and the aqueous phase was salted out. The organic phase was separated, dried (Na_2SO_4), filtered, and analyzed after silylation (BSTFA) by GC using *n*-tetradecane as an internal standard. The data pertaining to these experiments are tabulated in Table 2.[88]

Hydrogen Peroxide Oxidation of Medium- and Long-Chain Alkenes to Carboxylic Acids Catalyzed by Ia under Two-Phase Conditions with Added Solvent (Comparative Experiments). In a typical experiment, 1-decene (98% pure, 2.86 g, 20 mmol) was reacted for 6 h at 85 °C under stirring with the catalyst **Ia** (0.542 g, 0.24 mmol)/40% w/v H_2O_2 (9.35 mL, 110 mmol) oxidizing system in the presence of toluene (7.35 mL). At the end, after the usual workup the phases were separated. The amount of unconverted hydrogen peroxide was determined by iodometric titration of the aqueous layer. The organic layer was analyzed after silylation (BSTFA) by GC using *n*-tetradecane as an internal standard. Nonanoic acid was formed in 55% yield at 84% conversion of hydrogen peroxide (with 4−5% of the intermediate epoxide being unreacted), as compared to an isolated yield of 80% obtained in the absence of the solvent (Table 1, entry 2). When tetrachloroethane was used as a solvent under the same conditions, the formed C_9 acid dropped to 34% at 73% conversion of hydrogen peroxide (with 33% of the epoxide being unreacted).

Analogously, upon oxidation with **Ia** (0.2 mmol)/40% w/v H_2O_2 (88 mmol) in the presence of toluene (7.35 mL), *trans*-4-decene (20 mmol) after 8 h gave 24% of butanoic and hexanoic acid at 74% conversion of hydrogen peroxide, with 51% of the intermediate epoxide being unreacted (GC analysis, *n*-dodecane as an internal standard), as compared to an 80% and 77% yield of the same acids (after 6 h) obtained in the absence of the solvent (Table 1, entry 5). If tetrachloroethane was used as a solvent under the same conditions, the yield of the C_4 and C_6 acids fell to 16% at 84% conversion of hydrogen peroxide (with 70% of the epoxide being unreacted).

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[86] The pH_{app} of the 16% and 40% w/v hydrogen peroxide employed in these experiments was 3.3 and 2.2 (free acid as H_3PO_4, 20.6 and 48 mg/L, respectively).

[87] This value does not include the quota due to the phosphoric acid already contained in hydrogen peroxide itself (cf. ref 86).

[88] Through the use of procedure B (85 °C, 30 min) but with water alone in place of aqueous hydrogen peroxide, from cyclohexene and styrene oxides (**2e** and **2f**) the corresponding 1,2-diols were easily obtained in 85−86% yields (GC analysis). In contrast, from epoxyalkanes **2a,b** only small or negligible amounts of the respective 1,2-diols were formed under the same conditions.

[89] The GC−mass spectrum (as methyl ester) was consistent with published data.[71]

[90] Most of the glutaric and adipic acid formed (about 5% and 1%, respectively) is found in the mother liquor from acid extraction.

[91] The GC−mass spectrum (as dimethyl ester) was consistent with published data: Heller, J.; Yogev, A.; Dreiding, A. S. *Helv. Chim. Acta* **1972**, *55*, 1003.