Photocatalytic Oxygenation of Hydrocarbons with (Tetraarylporphyrinato)iron(III) Complexes and Molecular Oxygen. Comparison with Microsomal Cytochrome P-450 Mediated Oxygenation Reactions

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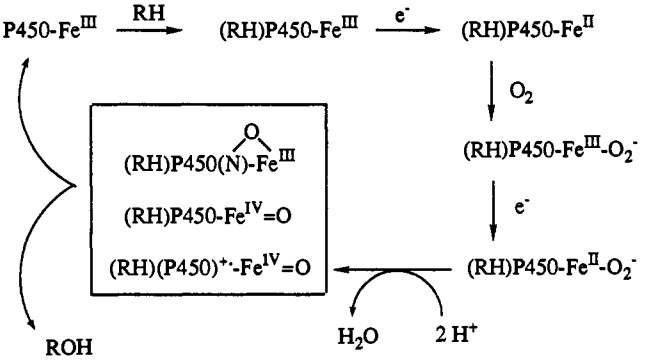
Abstract: Photocatalytic oxygenation of various alkenes with dioxygen and (5,10,15,20-tetraarylporphyrinato)iron(III) complexes yielded allylic oxygenation products and/or epoxides. The product composition was found to be influenced both by the nature of the used substrate and by the concentrations, as well as the axial ligands. Alkenes with strained carbon double bonds gave preferentially epoxides whereas mainly allylic oxygenation was observed for unstrained alkenes. The proposed reaction mechanisms involve the oxoiron(IV) porphyrinate (P)Fe^{IV}=O as the catalytically active species whose selectivity is related to that of the oxygenation of α-pinene with microsomal cytochromes P-450 and P-420 obtained from the yeast strain *Torulopsis apicola*. Oxygenation products observed with both systems give evidence for the occurrence of an oxoiron(IV) heme species in microsomal cytochrome P-450 mediated reactions. The enantio-, regio-, and chemoselectivities of the photooxygenation with iron(III) porphyrins and molecular oxygen are explained in terms of abstraction of an allylic hydrogen atom, catalyzed autoxidation and "direct" oxygen-transfer reactions.

Introduction

Catalytic oxygenation of hydrocarbons by molecular oxygen using metalloporphyrin catalysts, model reactions for the function of naturally occurring monooxygenase enzymes with iron porphyrin prosthetic groups, have attracted much attention in recent years. The catalytic system usually requires a reducing agent,[1] e.g. sodium borohydride[1b] or hydrogen/colloidal platinum,[1c] analogous to NADPH in enzymatic systems, to cleave the oxygen-oxygen bond in the intermediate dioxygen-iron porphyrin complex. The thus formed oxoferryl porphyrinate π cation radical (P)$^{+\cdot}$$Fe^{IV}$=O was stated to be analogous to the active species in the cytochrome P-450 monooxygenase oxygenation cycle. The chemistry of this "oxenoid" species has been studied in relation to the reactivity and chemo- and stereoselectivity of the catalytic system of cytochrome P-450.[2]

Recently, Groves and Watanabe[3] found evidence for two modes of O–O bond cleavage in (acyl peroxo)iron(III) porphyrins. In the presence of acidic protons or a polar solvent the acyl peroxo complex afforded the oxoferryl porphyrinate π cation radical by heterolytic O–O bond fission, whereas homolytic O–O bond cleavage afforded an iron(III) porphyrin *N*-oxide and/or the oxoiron(IV) porphyrinate complex under neutral conditions in apolar solvents. Similarly, competing homolytic and heterolytic mechanisms were proposed to operate in cytochrome P-450$_{CAM}$,

Scheme 1



where the intermediate peroxoiron(III) species is suggested to be activated by acylation prior to the formation of the active species[4] (Scheme 1). Homolytic O–O bond cleavage and therefore formation of the oxoiron(IV) porphyrinate and the *N*-oxide in the hydrophobic protein pocket of cytochrome P-450 enzymes should be taken into account if one draws a picture of the catalytic cycle of these monooxygenases.

Contrary to the well-studied, highly reactive oxoferryl porphyrinate π cation radical (P)$^{+\cdot}$$Fe^{IV}$=O, the isolable *N*-oxide was shown to be unreactive toward olefins. Whereas (P)$^{+\cdot}$$Fe^{IV}$=O is electronically analogous to compound I of horse radish peroxidase (HRP), the one-electron reduction product oxoiron(IV) porphyrinate (P)Fe^{IV}=O resembles the HRP compound II, which was characterized by means of UV–vis, NMR, and Mössbauer spectroscopy in comparison to model heme complexes.[5]

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Although several spectroscopic data are available for oxoiron(IV) porphyrins,[3,6] e.g. TTPFe^{IV}=O, only little is known about their chemistry. Moreover, no data are available that compare the chemoselectivity of oxoiron(IV) complexes with cytochrome P-450 mediated oxygenation reactions. Whereas reaction with triphenylphosphine,[6a] triphenylarsine,[6b] amines,[6d] and nitrosodurene[6c] yielded oxygenated products, attempts to obtain oxygenated olefins failed under thermal catalytic conditions[6e,7a] or were attributed to peroxyl[7b] or hydroxyl[7c] radicals. Moreover, there is a consensus that (P)Fe^{IV}=O is unable to epoxidize olefins.[7a] On the other hand, photocatalytic systems starting with chloro(tetraphenylporphyrinato)iron(III)[8a] or (μ-oxo)bis[(tetraphenylporphyrinato)iron(III)][8b] and cyclohexene yielded oxygenated products by abstraction of allylic hydrogen atoms by the oxoiron(IV) complex.[8]

Contrary to the very reactive radical cationic oxoiron(IV) porphyrinates which are easily obtained by treatment of iron(III) porphyrins with single oxygen donors like iodosobenzene, hypochlorite, peroxides, and peracids, hitherto no facile, clean way is known leading to the corresponding oxoiron(IV) porphyrinates exclusively avoiding other possibly oxidizing intermediates. Thus, iron(III) porphyrinates may be reduced either photolytically or chemically to iron(II), which gives with molecular oxygen the oxoiron(IV) species as an intermediate.[8] Trautwein *et al.*[6e-i] showed spectroscopically the occurrence of porphyrinato-containing oxoiron(IV) and oxoiron(IV) cation radicals during the reaction of the dioxygen adduct of iron(II) porphyrinates with tetrafluoroborate in different solvents. Alternatively, oxoferryl porphyrinates may be generated from iron(III) complexes with monooxygen donors under special reaction conditions.[3,6,7a] To study the reactivity of oxoiron(IV) porphyrinates we decided to use the photolytic generation from iron(III) porphyrinates and molecular oxygen in a catalytic cycle which was described by several authors and us.[8,9] Photocatalytic formation is started with a ligand-to-iron(III) electron transfer process upon irradiation in the wavelength range 350–440 nm leading to the reduced iron(II) and the oxidized ligand. In the presence of an oxidizable trap for radicals X$^{\cdot}$ fast recombination *via* back electron transfer may be diminished, and with dioxygen a μ-peroxo complex is formed which decomposes rapidly to the desired complex according to eqs 1–3. Finally, one observes the formation of the μ-oxo complex (eq 4) in the case of the tetraphenylporphyrinato ligand and a hydroxo complex (eq 5) by abstraction of hydrogen from the solvent in the case of sterically hindered porphyrins, e.g. tetramesitylporphyrin.[6c]

$$(P)Fe^{III}X \xrightarrow{h\nu} Fe^{II}(P) + X^{\cdot} \quad (1)$$

$$(P)Fe^{II} + O_2 \longrightarrow (P)Fe^{III}\text{-}O\text{-}O\text{-}Fe^{III}(P) \quad (2)$$

$$(P)Fe^{III}\text{-}O\text{-}O\text{-}Fe^{III}(P) \longrightarrow 2\,(P)Fe^{IV}=O \quad (3)$$

$$(P)Fe^{IV}=O + Fe^{II}(P) \underset{h\nu}{\rightleftharpoons} (P)Fe^{III}\text{-}O\text{-}Fe^{III}(P) \quad (4)$$

$$(P)Fe^{IV}=O + RH \longrightarrow (P)Fe^{III}OH + R^{\cdot} \quad (5)$$

Photodisproportionation of the formed μ-oxo complex (eq 4) in the presence of dioxygen leads to a catalytic cycle in which the oxoiron(IV) complex is formed continuously. However, eqs 1–4 represent only a part of the involved reactions in the system RH/Fe(P)/O_2/$h\nu$ which should be considered below in more detail.

To study the chemistry of oxoiron(IV) porphyrinates generated with the photocatalytic system one has to consider contributions of other possibly reactive species during the reaction event. This can be done either by direct spectroscopic detection of e.g. different oxometallo species involved in the reaction event[6e-i] or by indirect evidence as are typical reaction products of these intermediates with useful substrates. We used in this work different alkenes for trapping oxidizing species, particularly α-pinene, which reactivities and selectivities with other oxidation systems are well-known.

Experimental Section

Materials. Benzene and toluene were destilled from Na and passed through a molecular sieve. The water content of the solvents was determined by the Karl Fischer titration method. Cyclooctadienes (Aldrich), (+)-α-pinene and (–)-α-pinene (Merck), dicyclopentadiene (Schuchard), and 1,5-cyclodecadiene (Fluka) were passed through a neutral Al_2O_3 column before use to remove oxygenated impurities. All other cyclo- and 1-methylcycloalkenes were synthesized from the corresponding cycloalkanones by standard procedures. Nitrosodurene was obtained from Aldrich. Chloro(tetraphenylporphyrinato)iron(III) (TPPFeCl) (**1**), (μ-oxo)bis[(tetraphenylporphyrinato)iron(III)] ([TPPFe]$_2$O) (**2**), and chloro[tetra(2,4,6-trimethylphenyl)porphyrinato]-iron(III) (TMPFeCl) (**3**) were prepared by standard methods.[10] The cyclodextrin-linked porphyrin complex **4** was prepared according to ref 11. ^{1}H NMR (Bruker MSL 300 instrument, $CDCl_3$, δ): 2.15–2.30 (m, CH_2), 3.20–4.00 (m, H_{CD} and OCH_2), 4.98 (d, H_{CD}-1), 6.70–8.00 (m, ArH), 13.50 (pyrrole). ^{13}C NMR ($CDCl_3$, δ): 29.7 (1 C, OCH_2CH_2-CH_2O), 59.0 (CH_3O-6), 60.3 (CH_3O-2), 70.0 ($OCH_2CH_2CH_2O$), 70.3 (C_{CD}-5), 70.8 (C_{CD}-6), 71.6 ($OCH_2CH_2CH_2O$), 73.2 (C_{CD}-3), 82.0 (C_{CD}-2), 83.5 (C_{CD}-4), 101.3 (C_{CD}-1), 120.3 (C-2′, ArH), 126.8, 126.9, 127.6, 129.7 (C-5′, ArH), 134.7, 142.3, 145.1. UV–vis ($CHCl_3$, nm): 340 (4.61), 380 (4.68), 417 (5.01), 511 (4.15). IR (Specord M 80 instrument, KBr, cm^{-1}): 3410 (br, H_2O), 2960–2920 (br, CH), 1200–970 (br, C–O–C), 800 (s, porphyrin). Mass spectrum (Vacuum-Generator VG-ZAB-HSQ instrument, FAB, *m*-nitrobenzylic alcohol matrix): *m/e* 2092 (M^+, base); 1520 (M^+ – 3 2,6-di-*O*-methylglucose). ESR spectra were recorded on a Bruker ER 200 tt spectrometer while the sample was irradiated with visible light (>400 nm) from outside using a 100-W mercury lamp (Hanovia) and a cut-off filter.

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Photocatalytic Oxygenation Reactions. A solution of the corresponding alkene and the catalyst in benzene was irradiated with a 55-W tungsten halogen immersion lamp in a 50-mL, thermostated photoreactor. A stream (2 L h^{-1}) of dry air was passed through the solution over the reaction time of 8 h at 20 °C.

Preparation of Microsomes. *Candida apicola* (IMET 43747, syn. *Torulopsis apicola*) was cultivated on a medium described previously.[12] A mixture of glucose and *n*-hexadecane served as the carbon source. The yeast was grown in 8-L batch fermenter cultures (Biostat E; B. Braun, Melsungen, FRG). Cells of the stationary growth phase were harvested, and the microsomal membrane fraction was prepared according to literature procedures.[13] The microsomes were washed with 0.25 M sucrose and resuspended in the preparation medium. Application of this procedure resulted in complete conversion of cytochrome P-450 to cytochrome P-420 in the microsomal fraction, which was estimated by the method of Omura and Sato.[14] The final content of P-420 was 1.01 nmol/mg protein. In contrast to the cell disintegration by French press[13] the cell disruption by glass beads (0.45 mm; 4 times for 30 s) and the subsequent experimental protocol[15] provided microsomes haboring intact cytochrome P-450 with a final content 1.26 nmol (mg of protein)$^{-1}$. For UV–vis spectra of cytochrome P-450 or P-420 containing microsomes, see Figure 1.

Microsomal Oxygenation of α-Pinene. The incubations for the oxygenation assay contained microsomes (2.5 mg of protein), 200 mmol of potassium phosphate (pH 7.5), 167 μmol of NADPH, and 200 μmol of α-pinene. The final volume was 10 mL, and the incubation was 30 min on a rotary shaker (250 rpm) at 25 °C. In references either microsomes or NADPH was omitted. The reaction mixtures were extracted with ether, dried over Na_2SO_4, and concentrated under reduced pressure. Products were analyzed by gas chromatography after addition of *n*-decane as internal standard. Typically, 1 μmol of product was formed which corresponds to ca. 1000 turnovers/mol of cytochrome P-450. The detection limit was calculated to be 50 nmol for the outlined procedure. In an control experiment omitting the microsomes the autoxidation products were below 100 nmol.

Product Analysis of Oxygenation Reactions. Analysis was performed by quantitative ^{13}C NMR spectroscopy and computer analysis of the reaction mixtures[16] and quantitative capillary gas chromatography. ^{13}C NMR spectra (75.479 MHz) were recorded on 1 g samples dissolved in 1.5 mL of $CDCl_3$ with 50 mg of chromium(III) acetylacetonate on a Bruker MSL 300 spectrometer. Probes were analyzed in parallel by capillary gas chromatography on a Hewlett-Packard 5890 IIA instrument, using *n*-decane as internal standard. A 25-m fused silica CP-cyclodextrin-B-236-M-19 glass capillary column (Chrompack) was used for determination of the enantiomeric excess along with authentic samples of the corresponding homochiral pinene derivatives. Visible spectra were obtained with a Specord M40 spectrophotometer.

Results and Discussion

Photocatalytic System. Under photolytic conditions in the absence of oxygen one can observe the clean formation of the reduced iron(II) porphyrin complexes (λ_{max} = 420 nm) from different iron(III) porphyrinates (chloro–, chlorato–, oxalato–, azido–, and methoxy–$TPPFe^{III}$ complexes) in the presence of pinene or other substrates bearing abstractable hydrogen atoms (eq 1).[9c] Upon exposure to air, the μ-oxo complex **2** (λ_{max} = 408 nm) is formed instantaneously with loss of the axial ligand of the initial complex. During the photocatalytic oxygenation reaction with different alkenes only the UV–vis spectrum of **2** is observed. ESR spectra of the reaction mixture with added nitrosodurene showed the spin adducts of the corresponding alkyl radicals. The polychromatic quantum yield of the photoreduction reaction varies between 0.009 and ca. 10^{-6} for the azido complex and **2**, respectively, which may be enhanced up to 0.059 for the azido complex upon addition of isopropanol (7%) to the reaction mixture. Enhancement of the quantum yield with isopropanol may be explained by coordination with the iron center as outlined below.

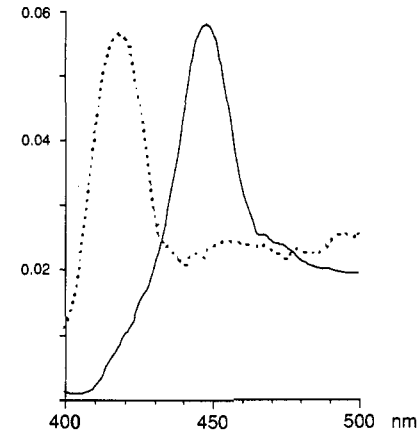

Figure 1. UV–vis spectrum of cytochrome P-450 (line) and cytochrome P-420 (dotted) containing microsomes of *T. apicola*. Spectra were taken after reduction with dithionite and treatement with carbon monoxide.

Table 1. Oxygenation of α-Pinene (**5**) with Different Oxidizing Species

	products (mol %)						
catalyst	**6**	**7**	**8**	**9**	**12**	**13**	**14**
t-BuOOH/O_2/$h\nu$[a]	25	18	16	9	16	16	
$TPPH_2$/O_2/$h\nu$[b]							99
TPPFeCl/PhIO[c]	91	9					
TPPFeCl/KO_2[d]							
m-ClC_6H_5COOH	100						
microsomes P-450/NADPH/O_2[e]	16	21		63			
microsomes P-420/NADPH/O_2[e]	51	11	16	22			
NADPH/O_2[f]							
T. apicola/O_2[g]		73	15	12			

[a] 0.1 mol of **5** and 2 mmol of *tert*-butyl hydroperoxide yields 3 mmol of product in benzene. [b] Reference 19. [c] Conditions: 10 mmol of **5**, 10 mmol of iodosobenzene, 20 μmol of **1** in 50 mL of benzene. The yield was 79% with respect to PhIO. [d] Conditions: 0.1 mol of α-pinene, 0.1 mol of potassium superoxide, 1 mmol of dibenzo-18-crown-6 and 20 μmol of catalyst in 50 mL of benzene. [e] See Experimental Section. [f] Without microsomes. [g] Whole cells of *T. apicola* (0.15 g dry weight) were used instead of microsomes; α-pinene oxide (**6**) is not stable under these conditions.

In the presence of pyridine, the photolytically stable $TPPFe^{II}(py)_2$ complex was formed (λ_{max} = 426 nm) as it was already described in the literature.[17] No change in visible spectra and hence no photoreductions were observed without substrates, using benzene as solvent. As already outlined,[9] one has to deal with a photocatalytic system according to eq 4. The nature of this disproportionation has been studied by time resolved spectroscopy by other authors.[9b]

Oxygenation of α-Pinene. Oxygenation reactions with α-pinene (**5**) may produce a wide variety of products which are characteristic for the given oxygenation mechanism (Table 1). The oxoiron(IV) porphyrinate cation radical $(P)^{+\cdot}Fe^{IV}{=}O$ obtained with TPPFeCl (**1**) and iodosobenzene yielded α-pinene oxide (**6**) with high but not 100% selectivity as it was reported earlier.[18] Reaction of α-pinene with singlet oxygen yields *trans*-pinocarveyl hydroperoxide (**14**) only.[19] With peracids *trans*-α-pinene oxide (**6**) is obtained with high selectivity and on industrial scale,[20] whereas in radical chain autoxidation a broad product mixture is obtained.[21] Radical chain reactions in the case of α-pinene are thought to be

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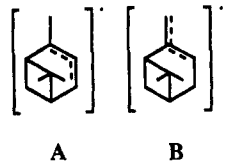
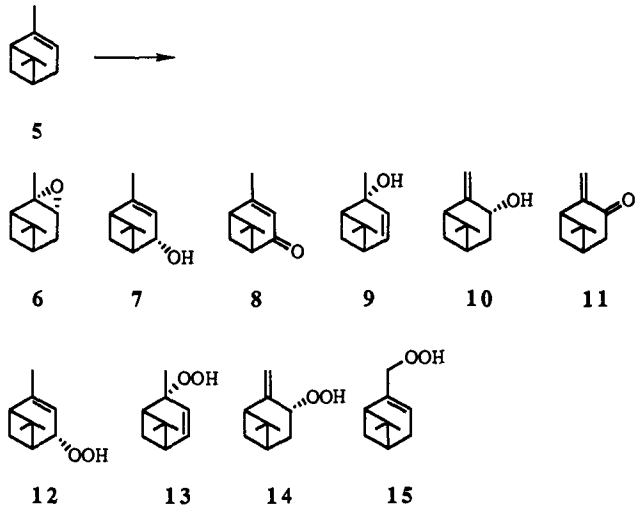


A B

Figure 2.



5 6 7 8 9 10 11

12 13 14 15

Figure 3.

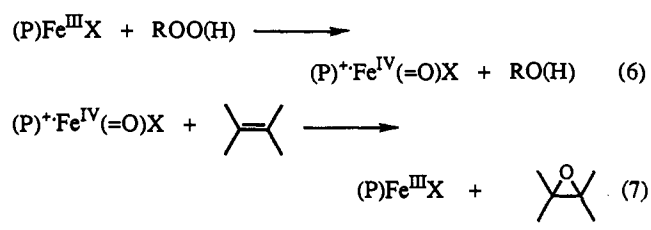
propagated *via* abstraction of allylic hydrogen atoms at the C-4 position or the allylic methyl group leading to allyl radicals **A** and **B**, respectively (Figure 2).

Whereas **B** is the kinetically favored radical, **A** is the thermodynamically more stable one which results in the formation of oxygenated products **7–9** (Figure 3). Products derived from the myrtenyl radical, e.g. hydroperoxide **15**, are not observed in thermal autoxidations[21a,b] but in sensitized photocatalytic autoxidations[21c] when singlet oxygen is involved.

Irradiating a solution of α-pinene (**5**) in the presence of TPPFeCl (**1**) and molecular dioxygen, we observed different product selectivities upon varying the substrate concentration. At high substrate concentration (2 M) and a substrate/catalyst ratio of 10 000, products of a controlled radical chain oxidation process were formed with high turnover numbers of up to 1500 (Table 2). Similar product compositions were found under identical conditions with $[TPPFe]_2O$ (**2**) and TMPFeCl (**3**) as well as with (tetraphenylporphyrinato)manganese(III),[22a] (tetraphenylporphyrinato)molybdate,[22b] and acetylacetonatoiron(III)[22c] complexes indicating a common oxidation mechanism which is largely independent of the used catalyst.

The role of the catalyst seems to be limited to induce radical chain reactions via hydrogen abstraction from **5** and to cleave hydroperoxyl radicals or hydroperoxides which are formed from radicals **A** or **B** *via* the known peroxide shunt mechanism.[23,24] Formation of peroxyl radicals from alkyl radicals (**A** or **B**) and molecular oxygen is very fast in radical chain autoxidation reactions whereas abstraction of hydrogen atoms by peroxyl radicals is usually the rate limiting step.[25c] We calculated pseudo-first-order formation rates of 0.077, 0.134, 0.073, and 0.109 h^{-1} mol^{-1} for **6–9** based on their portion in the product mixture determined by capillary gas chromatography. Bleaching of the catalyst monitored by UV–vis spectroscopy follows exponential decay kinetics depending on the used reaction conditions.

Intermediate hydroperoxides or hydroperoxyl radicals may react with **1** or **2** to give the corresponding oxoiron(IV) cation radical during the autoxidation event. Subsequent direct oxygen transfer to pinene along with formation of epoxide **6** (eqs 6 and 7) may be reduced using the sterically more crowded TMPFeCl (**3**) complex, which is reflected by a lower content of **6** in the reaction mixture compared to catalysts **1** and **2** (Table 2).



$$(P)Fe^{III}X + ROO(H) \longrightarrow (P)^{+\cdot}Fe^{IV}(=O)X + RO(H) \quad (6)$$

$$(P)^{+\cdot}Fe^{IV}(=O)X + \text{alkene} \longrightarrow (P)Fe^{III}X + \text{epoxide} \quad (7)$$

Peroxyl radical mediated autoxidation events strongly depend on substrate concentrations due to the different concentration dependence of the competing radical chain propagation *versus* radical chain termination. Using a lower substrate but the same catalyst concentration should hence favor the partition of characteristic oxoiron(IV) porphyrinate reaction products with the substrate in the reaction mixture. At low substrate concentration conditions (0.2 M) we observed indeed a changed product distribution with pinene as substrate (Table 2). Contrary to reactions with the corresponding manganese complexes[22a] where only allylic alcohols **7** and **9** were formed, α-pinene oxide (**6**) is the main product with iron porphyrinates **1** and **2** under photocatalytic conditions.

The water content of the solvent was found to be essential for product selectivities as well as for product yields of the photocatalytic oxygenation at low substrate concentration conditions. Using carefully dried benzene (water content below 0.001%) and dry air as an oxygen source, no reaction was observed probably due to the very low quantum yield of the photodisproportionation reaction. According to Peterson *et al.*[8b] and in agreement with the enhanced quantum yield upon addition of isopropanol to the reaction mixture, coordination of water to the iron center seems likely. Therefore, water should be initially necessary for an enhanced photoreduction reaction until enough alcohols are formed which may then coordinate as a sixth ligand to the iron center. To prove this, we used dry benzene and air with 10 equiv of **7** compared to the catalyst **2** in our photooxygenation and found the same oxygenation products and yields as with benzene which had a water content of 0.002%. Reactions reported in Table 2 were thus carried out in commercially available benzene (Merck) with a water content of about 0.002%. At higher water concentrations, breakdown of the selectivity of the photooxygenation favoring allylic oxygenation products **7** and **8** is observed, which one can attribute to an enhanced hydroxyl and hydroperoxyl radical formation as it was shown for molybdenum porphyrinates.[22b] However, destruction ("bleaching") of the catalyst due hydroxyl radicals is also strongly dependent on the water content of the solvent. Hydroperoxyl compounds **12** and **14** are known to form water and ketones **8** and **11**, respectively, in an autocatalyzed reaction. Therefore, at reaction conditions where efficient autoxidation is induced, the water content of the reaction mixture is also raised during the reaction and the catalyst is completely destroyed at maximum turnover rates of 1700. At low substrate concentrations only 10% of the catalyst was destroyed during 8 h of irradiation.

Addition of aprotic axial ligands like 1-methylimidazole to the reaction mixture first enhanced the reaction rate and at higher concentrations inhibited the turnover frequency most likely *via*

(22) (a) Weber, L.; Behling, J.; Haufe, G.; Hennig, H. *J. Prakt. Chem.* **1992**, *334*, 265. (b) Weber, L.; Haufe, G.; Rehorek, D.; Hennig, H. *J. Mol. Catal.* **1990**, *60*, 267. (c) Stich, R.; Weber, L.; Rehorek, D.; Hennig, H. *Z. Anorg. Allg. Chem.* **1991**, *600*, 211.

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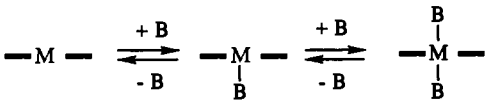
Table 2. Photocatalytic Oxygenation of α-Pinene (**5**) with Iron(III) Porphyrins in Benzene

catalyst	[S]/[C][a]	[S],[b] M	TO[c]	products (mol %) 6	7	8	9	10	11
TPPFeCl	20 000	2	1462	38	16	31	15		
TPPFeCl	10 000	2	1400	38	19	31	12		
$[TPPFe]_2O$	10 000	2	1500	38	16	31	15		
$[TPPFe]_2O$/RCOOH[d]	10 000	2	1348	38	16	31	15		
TMPFeCl	10 000	2	846	29	18	37	16		
TPPFeCl	1000	0.2	80	49	21	30			
$[TPPFe]_2O$	5000	2	700	41	11	36	12		
$[TPPFe]_2O$	1000	0.2	27	57	17	26			
TMPFeCl	1000	0.2	22	55	27	18			
$[TPPFe]_2O/TPPH_2$[e]	1000	0.2	27	53				4	43
$[TPPFe]_2O$/ImH[f]	1000	0.2	74	72	22		6		
$[TPPFe]_2O/H_2O$[g]	1000	0.2	90	31	31	38			
$[TPPFe]_2O$/MeIm[h]	1000	0.2	61	40	16	29	15		
TPPFeCl/MeIm[h]	1000	0.2	141	18	11	11	52	8	
TPPFeCl/MeIm[i]	1000	0.2	76	12	13	12	53	10	
TPPFeCl/MeIm[j]	1000	0.2	60	23	9	19	44	6	
k	0	2	0						

[a] Substrate **5** per catalyst ratio. [b] Concentration of **5** in mol/L. [c] Turnover/mol of product formed by 1 mol of catalyst. [d-j] The following additional substances were added to the reaction solution (equivalents related to catalyst): [d] 2-ethyl-hexanoic acid (20 equiv), [e] tetraphenylporphyrin (0.2 equiv), [f] imidazole (10 equiv), [g] water (20 equiv), and 1-methylimidazole [h] (1 equiv), [i] (5 equiv), and [j] (10 equiv). [k] No product was observed without catalyst under these experimental conditions.

Scheme 2



formation of the bis(methylimidazole)-ligated complex (Scheme 2, Table 2). The same observations were made in the case of oxoiron(IV) porphyrinato cation radicals; for a review see ref[1a]. The lower product selectivity which was not observed using manganese porphyrinates and 1-methylimidazole[22a] needs, however, further explanation.

Participation of the superoxid anion radical[25b] and its adduct $TPPFe(O_2^-)$,[26] which were demonstrated to be active oxidizing species, was considered as an alternative oxygenating species. However, the lack of any reaction product with pinene using iron(III) porphyrinates and potassium superoxide, both under thermal and photocatalytic reaction conditions, ruled out this possibility. Similarly, a primary outer-sphere electron transfer step[25b] resulting in a pinene cation radical must be ruled out because known products[25c] of this mechanism as are e.g. limonene and its oxygenated derivatives were not observed. An alternative primary oxygen iron porphyrin adduct was also shown[26] to give epoxides *via* formation of acylated oxoiron complexes with carboxylic acids. However, addition of a carboxylic acid to our photocatalytic system with **1** or **2** did not change the product composition in a significant way.

Addition of tetraphenylporphyrin $TPPH_2$ to the photocatalytic system with **2** demonstrates the effect of a possibly demetalated porphyrin during the reaction. $TPPH_2$ is a potent photosensitizer for $^1O_2$ generation, giving *trans*-pinocarveyl hydroperoxide[19] (**14**) in an ene reaction which again may serve as monooxygen donor for **2**. Subsequent generation of the oxoiron(IV) porphyrinato cation radical with hydroperoxides is well-known to yield epoxides.[25a] This reaction sequence is reflected by the formation of pinene epoxide (**6**) and pinocarvon (**11**) in approximately equal amounts using a mixture of **2** and $TPPH_2$ as catalyst (Table 2). Formation of singlet oxygen during the photocatalytic oxygenation with **2** and molecular oxygen can be therefore neglected because of the lack of the ene reaction pathway product **11** in the final reaction mixtures.

Enantioselective Photooxygenation of α-Pinene. The enantioselective oxygenation of unfunctionalized hydrocarbons is an attractive goal for a catalytic system which uses molecular oxygen as the oxidant. Several catalytic systems using chiral porphyrins and iodosobenzene as oxidant have been described[11a] with varying success. Similarly, cyclodextrin-linked porphyrinates or mixtures of cyclodextrins with porphyrinates have been used as oxygenation catalysts yielding products without discrimination between the enantiomers.[11b-d] Recently, we reported the enantioselective photooxygenation of a racemic mixture of *R*-(+)-**5** and *S*-(−)-**5** using the cyclodextrin linked porphyrin **4** (Figure 4) and molecular oxygen.[11e] The observed products along with their enantiomeric excesses (ee), depending on the solvent and the catalyst used, may provide further evidence for the mechanism of the photooxygenation reaction. Thus, photocatalytic oxygenation of α-pinene using the chiral porphyrin complex **4** as catalyst in acetone or acetonitrile as solvent gave higher enantiomeric discrimination between both pinene enantiomers as in benzene, probably due to the higher polarity of these solvents forcing the apolar pinene into the hydrophobic cyclodextrin cavity (Table 3). In all reactions with **4** oxygenation products derived from *S*-(−)-α-pinene were formed preferentially.

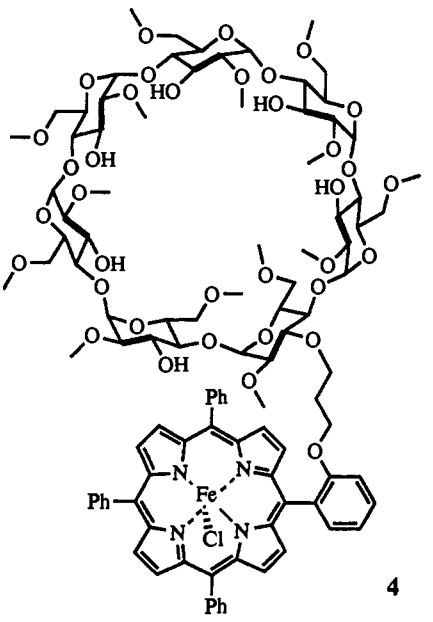


Figure 4.

The highest ee values were observed upon addition of 2-methylpyridine to the reaction mixture. We attribute this result to

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Table 3. Catalytic Oxygenation of a Racemic α-Pinene Mixture [(*S*)-(−)-α-Pinene/(*R*)-(+)-α-Pinene = 1/1][a]

			products, mol % (enantiomeric excess, ee, %)					
catalyst	solvent	TO	**6**	**7**	**8**	**9**	**10**	**11**
4/*hν*[a]	benzene	144	35 (5)	18 (5)	30 (6)	14 (4)	3 (10)	
4/*hν*[a]	acetonitrile	15	51 (11)	26 (18)	23 (3)			
4/*hν*[a]	acetone	16	29 (20)	26 (8)	17 (4)	14 (3)	8 (21)	6 (16)
4/2-MePy/*hν*[b]	benzene	4	41 (41)	11 (49)	10 (5)	9 (58)	11 (67)	9 (23)
FeTPPCl/DMCD/2-MePy/*hν*[c]	benzene	3	50 (51)	17 (6)	17 (7)		16 (11)	
4 + PhIO[d]	benzene	130	92 (5)	8 (5)				
microsomes P-450/NADPH/O_2[e]	water		16 (49)	21 (80)		63 (80)		
T. apicola/O_2[e]	water			73 (9)	15 (3)	12 (32)		

[a] Conditions: 10 μmol of **4** and 5 mmol of **5** were used in 50 mL of benzene. In all cases the products derived from the *S*-(−)-α-pinene were formed in excess. [b] 50 μmol of 2-methylpyridine was added. [c] 10 μmol of **1**, 50 μmol of 2,6-*O*-permethylated β-cyclodextrin, and 50 μmol of 2-methylpyridine were added to 50 mmol of **5**. [d] 10 μmol of **4** and 5 mmol of iodosobenzene were used to oxidize 5 mmol of **5**. [e] Conditions as in Table 1.

axial complexation with the metal center at the unprotected side of the porphyrin, lowering the overall turnover frequency as well as the participation of oxygenation reactions at the "achiral site" of **4**. Considering the retention times of the pinene enantiomers on chemically similar phases for gas chromatography, it was found earlier that on a per-(2,3,6-tri-*O*-methyl)-β-cyclodextrin-loaded apolar glass capillary column *R*-(+)-α-pinene is eluted later then the *S*-(−) enantiomer.[27a] However, using packed gas chromatography columns where cyclodextrin was dissolved in formamide, more similar to our photocatalytic reaction conditions, *S*-(−)-α-pinene showed an substantial increased retention time over its *R*-(−) enantiomer and hence higher tendency to form complexes with cyclodextrin.[27b] Although 1:1 inclusion complexes with cyclodextrins and their derivatives are well-known, it was not shown clearly whether increased retention times results from inside or also from outside binding of pinene to the cyclodextrin.[27c] NMR measurements of α-, β-, and γ-cyclodextrins with α-pinene in water showed preferential binding of the (*S*)-(−) enantiomer. The largest discrimination was found with α-cyclodextrin; the exchange frequency of free and bound pinene was slow compared to the NMR time scale.[27d]

The cooperative enzyme like "supramolecular" effect of **4** in pinene photooxygenation is demonstrated by comparing the ee values with the oxygenation reaction using TPPFeCl (**1**), 5 equiv of the corresponding permethylated β-cyclodextrin (DMCD), and 5 equiv of 2-methylpyridine as catalyst. Although the chiral component is present even in excess, the observed enantiomeric excess ratios are much lower then by using **4** as catalyst.

Alcohols **7**, **9**, and **10** are formed with high and approximately equal enantiomeric excess ratios, indicating thus a common oxygenation mechanism proceeding to a large extent at and/or in the cyclodextrin cavity of porphyrinate **4**. Formation of allylic alcohols from pinene either may proceed completely within the chiral cavity *via* the "oxygen rebound" mechanism and/or, alternatively, may involve enantioselective abstraction of the allylic hydrogen atom to yield after diffusion from the catalyst the free, chiral pinenyl radical intermediate (**A** or **B**). Upon addition of dioxygen the corresponding chiral peroxyl radicals may also induce an enantiodiscriminating autoxidation with pinene forming the chiral pinenyl radicals and hydroperoxides **12**–**15** assuming an excess of one radicalic enantiomer. However, this latter route should be ruled out because the typical autoxidation products verbenone (**8**) and pinocarvone (**11**), derived from **12** and **15** by loss of a water, are formed with much lower ee values than the alcohols giving evidence that the autoxidation reaction proceeds without substantial discrimination between the pinene enantiomers. We conclude therefore that partially there is involved rather a second, nonenantioselective reaction pathway *via* free radical chain oxidation. Similarly, enantioselective formation of pinene oxide **6** should proceed *via* a "direct" oxygen transfer mechanism mediated by the catalyst as it is described for the higher valent $(P)^{+\cdot}Fe^{IV}{=}O$ and as it is shown by our experiment using **4** and iodosobenzene giving the epoxide **6** with a small but measurable enantiomeric excess of 5%.

Table 4. Photocatalytic Oxygenation of *cis*-Cycloalkenes[a]

		products (mol %)		
alkene	TO	epoxide **16**	alcohol **17**	ketone **18**
cyclohexene[b]	64	21	35	
cyclohexene + **2**	625	4	28	68
cycloheptene[b]	45	29	33	38
cycloheptene + **2**	28	34	26	40
cyclooctene[b]	0			
cyclooctene + **2**	52	100		
norbornene[b]	559	100		
norbornene + **2**	841	100		

[a] Conditions: 0.1 mol of the corresponding alkene and 10 μmol of **2** in 30 mL of benzene were used. [b] Autoxidation reaction without catalyst. Turnovers were calculated on the basis of an imaginary amount of 10 μmol of catalyst to allow comparison of product yields.

Additionally, ESR measurements during the photolysis of **4** with the racemic pinene mixture and nitrosodurene showed strongly enhanced signals (two secondary pinenyl radical adducts with couplings to hydrogen atoms at C-α positions (g_1 = 2.0063 G, a_N = 13.25 G, a_H = 8.40 G; g_2 = 2.0063 G, a_N = 13.75 G, a_H = 7.25 G) and lines which were attributed to a tertiary pinenyl radical adduct) as compared to the reaction with **2**, most likely due to their prolonged lifetime in the cyclodextrin cavity.

Oxygenation of Cycloalkenes. The photooxygenation of different cycloalkenes and 1-methylcycloalkenes using iron porphyrins and molecular oxygen was already communicated.[8a,28] Some effort has been made to understand the relative rates of epoxidation using the iron(III) porphyrinate/PhIO system.[18] However, in the photocatalytic system using **2** and cycloalkenes with different ring sizes and, hence, different ring strains which should influence the reactivity of the double bond as well as the allylic hydrogen abstraction, we obtained very different epoxidation/allylic oxidation ratios (Tables 4 and 5). Autoxidation products using the same experimental conditions but without catalyst **2** are also displayed for comparison.

Clearly one can find that the larger the ring size the higher the yield of epoxides **16** and **19** (Figures 5 and 6). Interestingly, Groves and Watanabe[3a] also found cyclooctene oxide using cyclooctene as a substrate with (acyl peroxo)iron porphyrinates under thermal homolytic O–O bond cleavage conditions which they could not assign to an oxoferryl cation radical mediated epoxidation. In the light of our results this result may be explained in terms of an oxoferryl porphyrinate epoxidation. Most striking are the results obtained with 1,5-dimethylcycloocta-1,5-diene, which yield in the autoxidation only 11% of the epoxide beside substantial amounts of allylic peroxides and polyperoxides,

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(28) Weber, L.; Haufe, G.; Rehorek, D.; Hennig, H. *J. Chem. Soc., Chem. Commun.* **1991**, 502.

Table 5. Photocatalytic Oxygenation of 1-Methylcycloalkenes[a]

alkene	TO	products (mol %) 19	20	21	22	23	24	25	26
1-methylcyclopentene[b]	309	28	72						
1-methylcyclopentene + 2	1236	26	13	36	16	8			
1-methylcyclohexene[b]	420	12	5[c]	2	5[c]			17[c]	2
1-methylcyclohexene + 2	4026	10	14	25	15	19	9	8	
1-methylcycloheptene[b]	101	53	11[c]	11					
1-methylcycloheptene + 2	1503	61		29			10		
1-methylcyclooctene[b]	49		70				30		
1-methylcyclooctene + 2	300	100							
1,5-dimethylcycloocta-1,5-diene[b]	4233	11	*d*	*e*					
1,5-dimethylcycloocta-1,5-diene + 2	986	100 (10:1)[f]							

[a] Conditions: 0.1 mol of the corresponding alkene and 10 μmol of **2** in 30 mL of benzene were used. [b] Autoxidation reaction without catalyst. Turnovers were calculated on the basis of an imaginary amount of 10 μmol of catalyst to allow comparison of product yields. [c] Including the corresponding hydroperoxide. [d] 35% of six different allylic alcohols and 49% of three different peroxides were found along with [e] 5% of three ketones. [f] Mixture of mono- and bis(epoxide) (10:1).

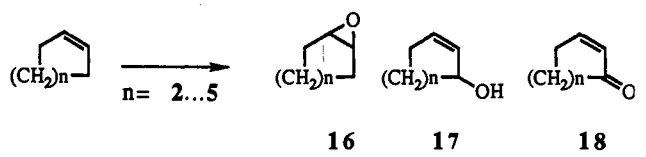

Figure 5.

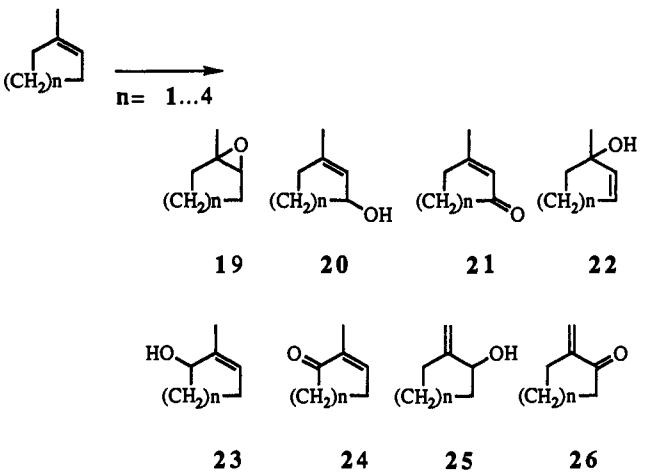

Figure 6.

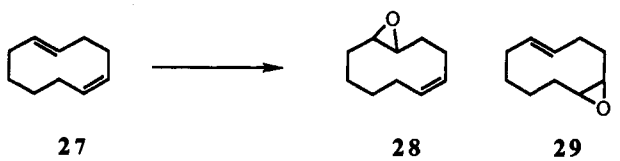

Figure 7.

whereas with **2** the mono- and bis(epoxide) are found exclusively (Table 5). This result suggest a reaction mechanism involving the porphyrinate **2** independent of the autoxidation of this olefins with molecular oxygen.[25b]

cis-Mono(epoxide) **29** (Figure 7) was obtained similarly as the sole product from *cis,trans*-cyclodeca-1,5-diene (**27**) using **2** as photocatalyst with high turnover numbers (975, conditions as in Table 4). No product was observed with **27** without catalyst **2** but under the same photolytic reaction conditions. The iron(III) porphyrinate cation radical system TPPFeCl/PhIO similarly afforded **29** in 67% yield relative to the iodosobenzene. The corresponding *trans*-mono(epoxide) **28** was reported in reactions with peracids,[29] which we could reproduce with *m*-ClC_6H_4-COOOH with 43% yield relative to the peracid. In the case of oxoferryl porphyrinato cation radicals $(P)^{+\cdot}Fe^{IV}{=}O$ the enhanced

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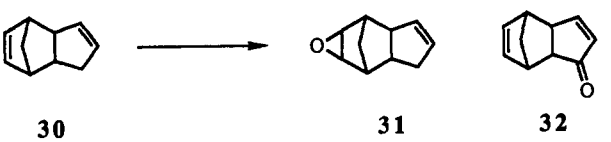

Figure 8.

epoxidation selectivity for *cis*-alkenes is attributed to a favored steric accessibility of the iron oxene moiety[30] by the double bond, which is not the case for the much smaller peracids.

Dicyclopentadiene (**30**) (Figure 8) gave the epoxide **31** and ketone **32** in 61% and 39% yield, respectively, using **1** as photocatalyst (TO = 612; conditions as in Table 4) (TO = turnover number). The autoxidation of **30** using various transition metal salts and complexes has been profoundly studied.[31]

As in the case of norbornene, which already in the autoxidation yields only the epoxide because of the lack of abstractable allylic hydrogen atoms (Table 4), alkyl peroxyl radicals are formed which are thought to epoxidize the very strained double bond in the norbornene moiety[25] resulting finally in the epoxide and after loss of an additional allylic hydrogen the allylic ketone **32**.

Traylor *et al.*[18] related the different epoxidation rates of the oxoiron(IV) porphyrinate cation radical with various alkenes to the alkene ionization potential. In our system this would predict higher epoxidation rates for α-pinene (8.07 eV) than for cyclooctene (8.98) and cyclohexene (9.00), which is clearly not the case (Tables 1 and 2). Instead, we compared the bond lengths and bond angles of the various cycloalkenes using Allingers MM2[32a] force field program (Table 6). The program yields formation enthalpies for cycloalkenes and cycloalkanes which are in excellent agreement with *ab initio* calculations as well as with experimental data.[32b,c] Moreover, an arbitrary "strain" energy is calculated which reflects the enthalpy difference compared to an unstrained acyclic alkene of the same constitution. Assuming 123.8° as an ideal bond angle and 0.1347 nm as an "unstrained" double bond (experimental values for *trans*-but-2-ene[32d]), double bonds with larger bond lengths and bond angles should be disfavored and hence are expected to be more easily epoxidized by a rather mild oxidizing agent. Examples for this tendency by using strained olefins are well documented.[25b] As one can see from Table 6, bond lengths and angles show only

(30) (a) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 507. (b) He, G.-X.; Mei, H.-Y.; Bruice, T. C. *J. Am. Chem. Soc.* **1991**, *113*, 5644.

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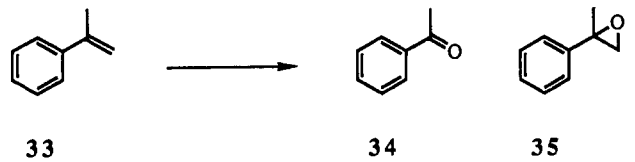
Table 6. Calculated Strain Energies,[a] Bond Lengths,[b] and Bond Angles[b] of Cycloalkenes

cycloalkene	E_{strain} (kcal/mol)	R_{bond} (nm)	bond angle 1	bond angle 2
cyclopentene	6.5	0.1337 (0.1343)	112.4 (111.0)	112.4 (111.0)
1-methylcyclopentene	4.9	0.1340	111.8	111.9
cyclohexene	2.3	0.1342 (0.1341)	122.8 (124.0)	122.8 (124.0)
1-methylcyclohexene	2.0	0.1344	121.7	123.2
cycloheptene	7.5	0.1342	123.4	123.4
1-methylcycloheptene	7.8	0.1345	123.2	121.7
cyclooctene	10.5	0.1344	125.0	124.1
1-methylcyclooctene	10.5	0.1346	125.3	122.8
1,5-dimethylcyclo-1,5-octadiene	15.2	0.1346	126.2	122.0
1,5-*cis*,*trans*-cyclodecadiene	12.0	0.1345 (cis)	126.0	125.7
		0.1340 (trans)	122.5	120.3
norbornene	20.8	0.1339 (0.1344)	107.3 (107.0)	107.3 (107.0)
α-pinene	33.6	0.1345 (0.1340)	119.1 (118.0)	117.2 (118.0)

[a] With program MMPI (QCPE).[32a] [b] In parentheses experimental values[32d-f] are given. Data were calculated for the most stable conformer.



33 34 35

Figure 9.

minor differences in cycloalkenes with different ring sizes and are thus not useful for correlations with their reactivities.

Comparing the calculated strain energies with epoxide/allylic oxidation ratios from Tables 4 and 5, one can indeed find that the larger the strain energy of the particular olefin the higher the yield (or portion in the product) of the epoxide in the photocatalytic oxygenation reaction. However, α-pinene may be regarded as an exception because the calculated high strain should reside mainly in the cyclobutane moiety of this bicyclic system.

Oxygenation of Other Alkenes. A very efficient induction of oxidation is observed with α-methylstyrene (**33**) (Figure 9). Photooxygenation with $(TPPFe)_2O$ at high concentration conditions afforded (TO = 3506, corresponding to 35% conversion) acetophenone (**34**) (44%) and the epoxide **35** (56%) as it was observed as well in autoxidation reactions at elevated temperatures.[25b]

Formation of **34** was explained[25b] in terms of a two-step dioxetane formation and subsequent cleavage of the carbon–carbon double bond. A product distribution closely related to radical chain autoxidation was also obtained with oct-1-ene using **2** as catalyst (TO = 71) involving the corresponding epoxide, allyl alcohols, and rearranged allyl alcohols.

Several olefins like styrene, β-methylstyrene, indene, and oct-2-ene were found to be unreactive under the photocatalytic conditions described above using **1** or **2** as catalyst. However, one might expect some oxygenated products on using other reaction conditions, e.g. higher catalyst concentrations, a more powerful irradiating light source, or an other photoreactor configuration.

Microsomal Oxygenation of α-Pinene. A large number of data is available dealing with whole cell culture oxygenation of α-pinene;[33] to our knowledge no exact data are available about cytochrome P-450 mediated oxygenation reactions. Therefore, we used the yeast strain *Torulopsis apicola*, which is known to have a well defined cytochrome P-450 system,[34ab] to isolate the microsomal cytochrome-containing fraction. In preliminary experiments we demonstrated that oxygenation products **6–11** are stable under incubation conditions with microsomes. Oxygenation of **5** with whole cells of *T. apicola* yielded, similarly to other yeast strains,[34c] *trans*-verbenol (**7**) as the main product, the epoxide being not stable under the conditions used.

Main products of the microsomal oxygenation with cytochrome P-450 are allylic alcohols **7** and **9**, both derived from pinene radical **A** (Table 1). *trans*-Pin-3-en-2-ol (**9**) is known to be the kinetic product in radical recombination reactions of **A**. Depending on the reaction conditions, **9** rearranges to **7**,[35] the main product in the oxygenation with whole cells of *T. apicola*. The ratio of allylic alcohols with the hydroxyl group at the primary hydrogen abstraction position (**7**, retention) and the rearranged alcohol (**9**) was found to be characteristic for P-450 as well as for $(P)^{+\cdot}Fe^{IV}{=}O$ mediated oxygenations.[36] We found substantial amounts of the rearranged alcohol **9** for both cytochrome P-450, cytochrome P-420, and the photocatalytic system with 1/1-methylimidazole. Again, the observed enantiomeric excess ratios (Table 2) show high ee values for alcohols **7** and **9** as well as for pinene oxide **6**. The principal similarities to the photooxygenation with the chiral porphyrin **4** are obvious. Microsomal oxygenation of β-pinene with cytochrome $P\text{-}450_{LM2}$ and phenobarbital induced rabbit microsomes reported by Groves *et al.*[36] yielded also β-pinene epoxide and the corresponding allylic oxygenation products.

However, although a large number of data are collected using iron porphyrins as cytochrome P-450 models, almost all of them lack the fifth thiolate ligand for the iron(III) central atom which is a characteristic feature of P-450 enzymes. Available iron porphyrinate models bearing the sulfur coordination have not been used hitherto in alkene oxygenation reactions.[37] Recently, it was shown that (not denaturated) cytochrome P-420 is not simply an inactive form of P-450 lacking the cystein thiolate ligation at the iron center but may be reconverted to P-450 by several substrates.[38] Moreover, an equilibrium between P-450 and P-420 forms was demonstrated[39] and evidence was presented that P-450 and P-420 cleave hydroperoxides homolytically

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contrary to peroxidases, which prefer heterolytic O–O bond cleavage reactions.[40] Site-directed mutagenesis of human myoglobin changing the proximal histidine to cysteine goes along with a change from homolytic to heterolytic O–O bond cleavage of cumene hydroperoxide.[41] Therefore, the role of thiolate coordination is thought to facilitate the heterolytic over the homolytic cleavage step as it was also shown with model porphyrinates.[3b] However, it seems not only likely that there are two modes of O–O bond cleavage in iron heme containing oxidases, but different oxygenating species may arise also from different coordination situations on the catalytic center. Therefore, we used nondenaturated microsomal P-420 to oxidize α-pinene and obtained even more α-pinene oxide **6** than allylic alcohols, a product composition very similar to those obtained with our simple photocatalytic system. According to the above outlined considerations O–O bond cleavage in microsomal cytochrome P-420 lacking the thiolate should proceed homolytically and may lead to a oxoferryl complex as in our photocatalytic system. To what extend this intermediate is involved under physiological conditions in the metabolization of xenobiotic substances is rather unclear and needs further investigations.

Conclusions

The photocatalytic oxygenation reaction using iron(III) porphyrinates as catalysts and molecular oxygen as the oxygen source seems to be a new, alternative oxygenation system for oxidizing suitable alkenes. However, the oxygenation may involve different reaction pathways depending both on the used alkene and reaction conditions: (i) Abstraction of an allylic hydrogen from the substrate followed by recombination of hydroxyl with the alkyl radical in the radical cage porphyrinate complex ("oxygen rebound"[36]) should be responsible for enantioselective formation of allylic alcohols (eq 8). (ii) Diffusion of alkyl radicals from the

$$(P)Fe^{IV}{=}O + RH \longrightarrow [(P)Fe^{III}\text{-}OH\cdots R^{\cdot}] \longrightarrow (P)Fe^{II} + ROH \quad (8)$$

radical cage porphyrinate complex and reaction with dioxygen yield a product spectrum similar to that from a controlled autoxidation. Epoxides are formed from intermediary hydroperoxyl radicals or hydroperoxides via *O*-transfer either from the peroxyl radicals themselves or via the porphyrin complexes. (iii) "Direct" epoxidation of strained alkenes by the oxoiron(IV) porphyrinate complex analogous to epoxidation reactions of the $(P)^{+\cdot}Fe^{IV}{=}O$ complex occurs. However, due to the lower oxidation state and, hence, lower electrophilicity of $(P)Fe^{IV}{=}O$ one observes a much smaller reactivity in oxygen transfer reactions compared to the corresponding oxoferryl cation radical complex.

Contrary to the very reactive oxoiron(IV) porphyrinate π cation radical $(P)^{+\cdot}Fe^{IV}{=}O$, which mainly epoxidizes alkenes, the one electron reduction product oxoiron(IV) porphyrinate $(P)Fe^{IV}{=}O$ shows a broad spectrum of oxygenation reaction pathways as does microsomal cytochrome P-450. Therefore, we believe that $(P)Fe^{IV}{=}O$ is an attractive candidate for an alternative and/or a competing analogous iron heme complex in cytochrome P-450 mediated oxygenation reactions.

Note Added in Proof: For the role of the related manganese(IV)–oxo species in oxidation of alkenes see ref 42.

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