Osmium-Catalyzed Dihydroxylation of Olefins Using Dioxygen or Air as the Terminal Oxidant

Christian Döbler, Gerald M. Mehltretter, Uta Sundermeier, and Matthias Beller*

Contribution from the Institut für Organische Katalyseforschung (IfOK) an der Universität Rostock e.V., Buchbinderstrasse 5-6, D-18055 Rostock, Germany

Received March 6, 2000

Abstract: The osmium-catalyzed dihydroxylation of various olefins using molecular oxygen or air as the stoichiometric oxidant is reported. Aromatic olefins yield the corresponding diols in good to excellent chemoselectivities under optimized pH conditions (pH = 10.4−12.0). Air can be used under moderate pressures (3−9 bar) instead of dioxygen as the reoxidant. By increasing the oxygen content of the solution, it is possible to achieve highly efficient conversion at low catalyst amount (catalyst/substrate = 1:4000). Tri- and tetrasubstituted olefins are oxidized at pH > 11 to give the corresponding 1,2-diols in good to very good yields without requiring the addition of sulfonamides or other hydrolysis agents. Studies of the dihydroxylation of functionalized olefins demonstrate that the reaction conditions tolerate a variety of functional groups. In the presence of dihydroquinine or dihydroquinidine derivatives (Sharpless ligands), asymmetric dihydroxylations occur with lower enantioselectivities than tose of the classical $K_3[Fe(CN)_6]$ reoxidation system.

Introduction

Nearly 80% of all reactions performed in the chemical industry are oxidations or reductions. The most economically attractive as well as environmentally friendly oxidation reagents for bulk oxidation processes are either air or molecular oxygen. Current industrial processes using oxygen include the oxidation of BTX aromatics or alkanes to give carboxylic acids and the conversion of ethylene into ethylene oxide.[1] Most oxidation reactions in industry using oxygen are atom efficient processes, but they require drastic conditions and often proceed via radical processes.[2] Thus, the scope of these reactions, with respect to the substrate, is not very broad. To use oxygen for oxidation reactions under milder conditions, synthetic organic chemists have developed a number of methods involving the use of a stoichiometric amount of a coreductant.[3] Unfortunately, these methods produce in general overstoichiometric amounts of waste, which should be avoided nowadays even on a laboratory scale. Despite the advantage of air or dioxygen as the final oxidant, there are relatively few methods known which use homogeneous catalysts in the presence of oxygen under mild conditions.[4]

Because of this lack of knowledge, we started a program to develop atom efficient catalytic oxidation reactions for the refinement of olefins. Initially, we were interested in the direct synthesis of 1,2-diols from olefins. Special 1,2-diols, e.g., ethylene glycol and propylene glycol, are manufactured on a million ton scale per annum.[5] A number of 1,2-diols such as 2,3-dimethyl-2,3-butanediol, 1,2-octanediol, 1,2-hexanediol, 1,2-pentanediol, and 1,2- and 2,3-butanediol are interesting for fine chemical applications. At present they are produced in industry by a two-step sequence consisting of epoxidation of the terminal olefin with a peracid followed by hydrolysis of the resulting epoxide.[6] In addition, chiral 1,2-diols are of interest as intermediates for pharmaceuticals and agrochemicals.

With regard to its general applicability, the OsO_4-catalyzed dihydroxylation of olefins[7] is probably the most powerful tool to synthesize 1,2-diols and diol derivatives (Scheme 1).

The synthetic utility of the osmium-catalyzed dihydroxylation has been significantly enhanced in recent years. Especially the introduction of a general catalytic asymmetric dihydroxylation procedure by Sharpless and co-workers[8] led to an increasing number of applications in organic synthesis.[9]

The primary products formed by the reaction of OsO_4 with olefins are dimeric osmium(VI) glycolates, which are then able to react further to yield a 1,2-diol and an osmium(VI) species.

* Corresponding author. e-mail: matthias.beller@ifok.uni-rostock.de.

(1) Weissermel, K.; Arpe, H.-J. *Industrielle Organische Chemie*, 5th ed.; Wiley-VCH: Weinheim, 1998.

(2) (a) Fischer, R. W.; Röhrscheid F. In *Applied Homogeneous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; pp 439−464. (b) Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981. (c) Partenheimer, W. In *The Activation of Dioxygen and Homogeneous Catalytic Oxidation*; Barton, D. H. R., Martell, A. E., Sawyer, D. T., Eds.; Plenum: New York, 1993.

(3) (a) Review: Mukaiyama, T.; Yamada, T. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 17−35. (b) Mandal, A. K.; Iqbal, J. *Tetrahedron* **1997**, *53*, 7641−7648. (c) Iwahama, T.; Sakaguchi, S.; Ishii, Y. *Chem. Commun.* **1999**, 727−728.

(4) (a) Groves, J. T.; Qinn, R. *J. Am. Chem. Soc.* **1985**, *107*, 5790−5792. (b) Montanari, F., Casella, L., Eds. *Metalloporphyrins Catalyzed Oxidations*; Kluwer: Dordrecht, 1994. (c) Markó, J. E.; Giles, P. R.; Tsukazaki, M.; Chellé-Regnant, I.; Urch, C. J.; Brown, S. M. *J. Am. Chem. Soc.* **1997**, *119*, 12661−12662. (d) Peterson, K. P.; Larock, R. C. *J. Org. Chem.* **1998**, *63*, 3185−3189. (e) Coleman, K. S.; Lorber, C. Y.; Osborn, J. A. *Eur. J. Inorg. Chem.* **1998**, 1673−1675. (f) Christoffers, J. *J. Org. Chem.* **1999**, *64*, 7668−7669.

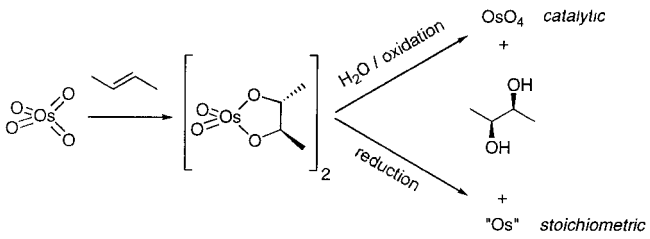
(5) Worldwide production capacities for ethylene glycol in 1995: 9.7 Mio to/a; worldwide production of 1,2-propylene glycol in 1994: 1.1 Mio to/a; Weissermel, K.; Arpe, H.-J. *Industrielle Organische Chemie*, 5th ed.; Wiley-VCH: Weinheim, 1998; p 167 and p 302.

(6) (a) Szmant, H. H. *Organic Building Blocks of the Chemical Industry*; Wiley: New York, 1989; p 347. (b) Pohl, G.; Gaube, H. In *Ullmann's Encyclopedia of Industrial Chemistry*; VCH: Weinheim, 1985; Vol. A1, pp 305−320.

(7) Reviews: (a) Schröder, M. *Chem. Rev.* **1980**, *80*, 187−213. (b) Kolb, H. C.; Van Nieuwenhze, M. S.; Sharpless, K. B. *Chem. Rev.* **1994**, *94*, 2483−2547. (c) Beller, M.; Sharpless, K. B. In *Applied Homogeneous Catalysis*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; pp 1009−1024. (d) Kolb, H. C.; Sharpless, K. B. In *Transition Metals for Organic Synthesis*; Beller, M., Bolm, C., Eds.; VCH-Wiley: Weinheim, 1998; Vol. 2, pp 219−242. (e) Marko, I. E.; Svendsen, J. S. In *Comprehensive Asymmetric Catalysis II*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; pp 713−787.

10.1021/ja000802u CCC: $19.00
Published on Web 10/07/2000

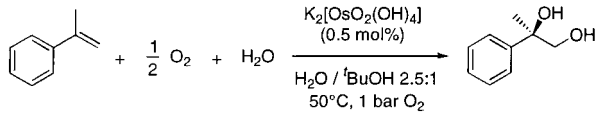
Scheme 1. Osmylation of Olefins



Because of the toxicity and the cost of osmium compounds, several efficient reoxidation processes of Os(VI) have been developed in the past. Initially chlorates[10] and hydrogen peroxide[11] were applied as cooxidants, both of which lead, in general, to reactions with low selectivity. However, very recently, Bäckvall and co-workers solved this problem elegantly by using *N*-methylmorpholine together with flavin as cocatalysts in the presence of hydrogen peroxide.[12] Other reoxidants which minimize side reactions are *tert*-butyl hydroperoxide in the presence of Et_4NOH[13] or *N*-oxides such as *N*-methylmorpholine *N*-oxide (NMO)[14] (Upjohn process) and trimethylamine *N*-oxide. $K_3[Fe(CN)_6]$ was introduced as a reoxidant for osmium(VI) species in 1975,[15] which was re-invented in 1990.[16] On the basis of the substantial improvement of enantioselectivities in asymmetric dihydroxylations by using $K_3[Fe(CN)_6]$ as the oxidant, industrial research led to the development of an in situ electrochemical reoxidation of $K_4[Fe(CN)_6]$.[17]

The most attractive reagents for the reoxidation of Os(IV) are air or dioxygen, since they are the most inexpensive and environmentally friendly oxidants. While former publications[18] and patents[19] demonstrate that in the presence of OsO_4 and oxygen mainly nonselective oxidation reactions take place, Krief et al. designed successfully a reaction system consisting of oxygen, catalytic amounts of OsO_4 and selenides for the dihydroxylation of α-methylstyrene under irradiation with visible light.[20] Recently, we reported that the osmium-catalyzed dihydroxylation of simple aliphatic and aromatic olefins proceed efficiently in the presence of dioxygen.[21] Outlined herein are new applications of this oxidation reaction, e.g., the dihydroxylation of tri- and tetrasubstituted olefins as well as functionalized olefins, dihydroxylations using air, and a study of catalyst efficiency for this dihydroxylation procedure.

Scheme 2. Osmium-Catalyzed Dihydroxylation of α-Methylstyrene with Dioxygen



Results

Dihydroxylation of Aromatic Olefins. Aromatic olefins are important substrates for the synthesis of pharmaceutically interesting 1,2-diols.[22] As demonstrated by our initial investigations, OsO_4 catalyzes the dihydroxylation of aromatic olefins in the presence of dioxygen. At present, the influence of the pH value and the ligands are not known in detail for this class of substrates. Hence, for our initial investigations we chose to study the dihydroxylation of α-methylstyrene as a model system (Scheme 2).

All catalytic experiments were conveniently carried out in Schlenk tubes using an oxygen atmosphere above the solution. A mixture of *tert*-butyl alcohol and water was used as the solvent system throughout our study. The pH of the mixture was kept constant by using different phosphate buffer systems (see Experimental Section for details). The reactions were followed by measuring the oxygen uptake with a graduated gas buret. In all cases of chemoselective reactions, approximately 1 mmol of dioxygen was consumed per 2 mmol of olefin.

In agreement with our previous results for terminal aliphatic olefins, the dihydroxylation of α-methylstyrene is dramatically influenced by the pH of the solution. In the absence of ligand, the best chemoselectivity (92%) at total conversion is obtained at pH 10.4 (Table 1, entries 1−4). The pH of the solution affects not only the chemoselectivity but also the rate of the reaction. The turnover frequency (TOF[23]) decreases from approximately 15 to 7 to 0.8 h^{-1} when the pH value is increased from 10.4 to 11.2 to 13.0. Interestingly, the addition of 0.5 mol % of DABCO as ligand increases the chemoselectivity of the reaction from 92% to 97%; however the overall rate is decreased slightly (TOF = 14 h^{-1} at pH 10.4, entry 5). When the amount of ligand is increased to 1.5 mol %, a further decrease of rate is observed. This effect is even more significant with the Sharpless ligand $(DHQD)_2PHAL$ (TOF = 12 h^{-1}, entries 8, 10, 13, and 14). The adverse effect of the ligand concentration on the reaction rate is in contrast to the ligand accelerated catalysis principle[24] observed for similar reactions using other reoxidants and is explained by the fact that the ligand slows down the turnover-limiting step (see Discussion).

(8) (a) Hentges, S. G.; Sharpless, K. B. *J. Am. Chem. Soc.* **1980**, *102*, 4263−4265. (b) Sharpless, K. B.; Amberg, W.; Bennani, Y. L.; Crispino, G. A.; Hartung, J.; Jeong, K.-S.; Kwong, H.-L.; Morikawa, K.; Whang, Z.-M.; Xu, D.; Zhang, X.-L. *J. Org. Chem.* **1992**, *57*, 2768−2771.

(9) (a) Nambu, M.; White, J. D. *Chem. Commmun.* **1996**, 1619−1620. (b) Mori, K.; Takikawa, H.; Nishimura, Y.; Horikiri, H. *Liebigs Ann./Recueil* **1997**, 327−332. (c) Sinha, S. C.; Sinha, A.; Sinha, S. C.; Keinan, E. *J. Am. Chem. Soc.* **1998**, *120*, 4017−4018. (d) Trost, B. M.; Calkins, T. L.; Bochet, C. G. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2632−2635. (e) Harris, J. M.; Keranen, M. D.; O'Doherty, G. A. *J. Org. Chem.* **1999**, *64*, 2982−2983. (f) Corey, E. J.; Guzman-Perez, A.; Noe, M. C. *J. Am. Chem. Soc.* **1994**, *116*, 12109−12110. (g) Corey, E. J.; Guzman-Perez, A.; Noe, M. C. *J. Am. Chem. Soc.* **1995**, *117*, 10805−10816. (h) Corey, E. J.; Noe, M. C.; Ting, A. Y. *Tetrahedron Lett.* **1996**, *37*, 1735−1738.

(10) Hofmann, K. A. *Chem. Ber.* **1912**, *45*, 3329−3336.

(11) (a) Milas, N. A.; Sussmann, S. *J. Am. Chem. Soc.* **1936**, *58*, 1302. (b) Milas, N. A.; Trepagnier, J.-H.; Nolan, J. T.; Iliopulos, M. I. *J. Am. Chem. Soc.* **1959**, *81*, 4730−4733.

(12) Bergstad, K.; Jonsson, S. Y.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **1999**, *121*, 10424−10425.

(13) Sharpless, K. B.; Akashi, K. *J. Am. Chem. Soc.* **1976**, *98*, 1986−1987.

(14) (a) Schneider, W. P.; McIntosh, A. V. (Upjohn) US-2.769.824, 1956; *Chem. Abstr.* **1957**, *51*, 8822e. (b) Van Rheenen, V.; Kelly, R. C.; Cha, D. Y. *Tetrahedron Lett.* **1976**, *17*, 1973−1976. (c) Ray, R.; Matteson, D. S. *Tetrahedron Lett.* **1980**, *21*, 449−450.

(15) Singh, M. P.; Singh, H. S.; Arya, A. K.; Singh, A. K.; Sisodia, A. K. *Indian J. Chem.* **1975**, *13*, 112.

(16) Minamoto, M.; Yamamoto, K.; Tsuji, J. *J. Org. Chem.* **1990**, *55*, 766−768.

(17) (a) Gao, Y.; Zepp, C. M. (Sepracor Inc.) WO-9.317.150, 1994; *Chem. Abstr.* **1994**, *120*, 119437j. (b) Anon. *Chem. Eng. News* **1994**, *72*, 41. (c) Torii, S.; Liu, P.; Tanak, H. *Chem. Lett.* **1995**, 319−320.

(18) Cairns, J. F.; Roberts, H. L. *J. Chem. Soc. C* **1968**, 640−642.

(19) (a) Celanese Corp., GB-1,028,940, 1966; *Chem. Abstr.* **1966**, *65*, 3064f. (b) Myers, R. S.; Michaelson, R. C.; Austin R. G. (Exxon Corp.) US-4496779, 1984; *Chem. Abstr.* **1984**, *101*, P191362k.

(20) Krief, A.; Colaux-Castillo, C. *Tetrahedron Lett.* **1999**, *40*, 4189−4192.

(21) Döbler, C.; Mehltretter, G.; Beller, M. *Angew. Chem., Int. Ed.* **1999**, *38*, 3026−3028.

(22) Selected examples: (a) Li, G.; Chang, H.-T.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 451−454. (b) Curran, D. P.; Ko, S.-B. *J. Org. Chem.* **1994**, *59*, 6139−6141. (c) Fang, F. G.; Xie, S.; Lowery, M. W. *J. Org. Chem.* **1994**, *59*, 6142−6143. (d) Whang, Z.-M.; Kolb, H. C.; Sharpless, K. B. *J. Org. Chem.* **1994**, *59*, 5104−5105. (e) Fisher, A. J.; Kerrigan, F. *Synth. Commun.* **1998**, *28*, 2959−2968.

(23) TOF = mol product × mol catalyst^{-1} × h^{-1}

(24) Berrisford, D. J.; Bolm, C.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1059−1070.

Table 1. Dihydroxylation of α-Methylstyrene[a]

entry	ligand	L/Os	[L] [mmol/l][b]	pH[c]	time [h]	yield [%]	selectivity [%]	ee [%]
1				9.5	24	75	90	
2				10.4	12	92	92	
3				11.2	24	84	92	
4				13.0	24	9	40	
5	DABCO[f]	1:1	1	10.4	14	97	97	
6	DABCO	3:1	3	10.4	16	97	97	
7	DABCO	3:1	3	11.2	24	93	97	
8	$(DHQD)_2PHAL$[g]	1:1	1	10.4	16	96	96	75
9	$(DHQD)_2PHAL$	3:1	3	9.5	24	33	94	84
10	$(DHQD)_2PHAL$	3:1	3	10.4	20	96	96	80
11	$(DHQD)_2PHAL$	3:1	3	11.2	23	97	97	76
12	$(DHQD)_2PHAL$	3:1	3	13.0	24	10	45	17
13	$(DHQD)_2PHAL$	6:1	6	10.4	20	60	97	85
14	$(DHQD)_2PHAL$	30:1	30	10.4	20	34	97	85
15[d]	$(DHQD)_2PHAL$	3:1	3	10.4	24	30	94	86
16[e]	$(DHQD)_2PHAL$	3:1	3	10.4	68	14	93	88 (94)[k]
17	$(DHQD)_2PYR$[h]	3:1	3	10.4	21	95	95	43 (69)[k]
18	$(DHQD)_2AQN$[i]	3:1	3	10.4	21	96	96	65 (82)[k]
19	(DHQD)PHN[j]	6:1	6	10.4	21	94	94	42
20[l]	$(DHQD)_2PHAL$	1:1	100	10.4	24	98	98	88

[a] Reaction conditions: 2 mmol of α-methylstyrene, 0.5 mol % of $K_2[OsO_2(OH)_4]$, 50 °C, 1 bar of O_2, 25 mL of buffer solution, 10 mL of *t*-BuOH. [b] The given concentration of the ligand is based on the assumption that the ligand is entirely located in the organic phase. [c] The given value is the pH of the aqueous buffer solution at the beginning of the reaction. In most cases the pH of the aqueous phase remains constant during reaction. [d] Reaction carried out at 40 °C. [e] 30 °C. [f] 1,4-Diazabicyclo[2.2.2.]octane. [g] Hydroquinidine 1,4-phthalazinediyl diether. [h] Hydroquinidine 2,5-diphenyl-4,6-pyrimidinediyl diether. [i] Hydroquinidine (anthraquinone-1,4-diyl) diether. [j] Hydroquinidine 9-phenanthryl ether. [k] Best ee values reported in the literature, see ref 7. [l] 100 mol % of OsO_4 to determine the ceiling ee.

Table 2. Dihydroxylation of α-Methylstyrene under Pressure[a]

entry[b]	pressure [bar][c]	cat. [mol %]	ligand	L/Os	[L] [mmol/l]	yield [%]	selectivity [%]	ee [%]
1	3	0.1	DABCO	3:1	1.5	83	95	
2	3	0.1	DABCO	3:1	1.5	95[d]	95	
3	5	0.1	DABCO	3:1	1.5	94	94	
4	5 (air)	0.1	DABCO	3:1	1.5	41	93	
5	9 (air)	0.1	DABCO	3:1	1.5	76	92	
6	3	0.1	$(DHQD)_2PHAL$	3:1	1.5	95[d]	95	60
7	1	0.1	$(DHQD)_2PHAL$	15:1	3	86	95	82
8	3	0.1	$(DHQD)_2PHAL$	15:1	3	93	93	79
9	5	0.05	$(DHQD)_2PHAL$	15:1	1.5	94	94	78
10	5	0.033	$(DHQD)_2PHAL$	15:1	1	93	93	77
11	10	0.025	$(DHQD)_2PHAL$	15:1	0.8	71	93	76

[a] Reaction conditions: $K_2[OsO_2(OH)_4]$, 50 °C, 25 mL of buffer solution (pH 10.4), 10 mL of *t*-BuOH, 24 h. [b] Entry 1, 6:5 mmol olefin; entries 7−11, 2 mmol olefin. [c] The autoclave was purged with O_2 and then pressurized to the given value. [d] Reaction time 48 h.

To study the asymmetric catalytic dihydroxylation in the presence of dioxygen, we performed several reactions using different cinchona-derived ligands. Sharpless et al. reported an enantioselectivity of 94% for the dihydroxylation of α-methylstyrene with $(DHQD)_2PHAL$ as the ligand using $K_3[Fe(CN)_6]$ as reoxidant at 0 °C.[8b] However, at 50 °C and at pH 10.4 in the presence of 5 mol % of $(DHQD)_2PHAL$, an enantioselectivity of 88% ee is obtained. Table 1 (entries 8−19) shows that under our conditions the enantioselectivity is influenced by the ligand concentration, the temperature, and the pH value. The highest enantioselectivities are observed at low pH, high ligand concentration, and low temperature. Hence, at 30 °C (Os/L = 1:3; pH = 10.4) an ee of 88% is obtained. However, at 30 °C the reaction is significantly slower compared to 50 °C. At 50 °C, an 85% ee was realized by increasing the ligand concentration to Os/L = 1:6. A further increase in the ligand concentration (Os/L = 1:30) does not lead to a further increase of enantioselectivity. The ceiling ee at 50 °C was determined to be 88% (Table 1, entry 20). Among the different cinchona alkaloid ligands tested, the phthalazine derivative gave the best ee values (Table 1, entries 8−16). This is similar to reactions with $K_3[Fe(CN)_6]$ as reoxidant.[7d]

Next, we were interested in the influence of the dioxygen concentration on the catalyst efficiency. As shown in Table 2, the reaction rate is significantly improved by working at 3−10 bar of dioxygen pressure. We did not perform reactions at dioxygen pressures above 10 bar due to safety reasons;[25] however it is highly probable that at elevated pressures even higher reaction rates are possible. It is worth noting that there is no decrease in chemoselectivity at higher pressures compared to those of the corresponding reaction at 1 bar.

Using a catalyst-to-substrate ratio of 1:1000 in the presence of DABCO as ligand (Os/L = 1:3), the reaction reaches 87% conversion after 24 h at 3 bar, while at 5 bar total conversion (TOF = 39 h^{-1}) is observed after the same time (Table 2, entries 1 and 3). Despite the low amount of OsO_4, the catalyst is not deactivated even after 24 h and the reaction proceeds to total conversion (Table 2, entry 2). Because of the positive influence of pressure, we thought that air would also be able to be employed as the reoxidant. The use of air instead of dioxygen would constitute a significant improvement with regard to safety issues, applicability, and economics. Indeed, the catalytic dihydroxylation takes place in the presence of air (Table 2, entries 4 and 5). As one would expect, the rate of the reaction is decreased; nevertheless 83% conversion (92% chemoselectivity) of α-methylstyrene is observed at 9 bar within 24 h. These

(25) **Caution**: At elevated pressures and temperatures, the *t*-BuOH/oxygen vapors above the reaction mixture can enter an explosive regime.

preliminary results will be of special importance for larger scale dihydroxylations (>1 kg). For laboratory syntheses on a mmol scale, we recommend the procedure using dioxygen at atmospheric pressure which is carried out more conveniently.

For the asymmetric dihydroxylations under pressure (Table 2, entries 6−11), we noted that a larger amount of ligand (L/Os = 15:1) is necessary, to obtain enantioslectivites of 80% ee, when the catalyst amount is reduced to 0.1 mol % or lower. This is explained by the fact that under given conditions (temperature, solvents, etc.) the enantioselectivity of asymmetric dihydroxylations is influenced by the concentration of the chiral ligand in the organic phase.

Also in the presence of chiral ligands there is a clear correlation between catalyst activity and dioxygen pressure. The best catalyst turnover frequency of ca. 120 h^{-1} is obtained at 10 bar (Table 2, entry 11). This catalyst activity could be already of interest for fine chemical application;[26] however, the requirements for the application of the procedure in bulk processes have not yet been met.

To understand the extent to which the structure of the aromatic olefin alters the reactivity in the catalytic dihydroxylation with dioxygen, we studied the reactions of styrene, 4-methoxystyrene, 4-chlorostyrene, 2-vinylnaphthalene, 1-phenyl-1-cyclohexene, and *trans*-stilbene in detail (Table 3).

It is important to note that the chemoselectivity of the substrates decreases in the following order: α-methylstyrene > 4-methoxystyrene > 4-chlorostyrene > 1-phenyl-1-cyclohexene > styrene > 2-vinylnaphthaline > *trans*-stilbene. There is no clear correlation between the olefin structure and the observed chemoselectivities at pH 10.4−11.2; however the chemoselectivity decreases significantly at pH 13 for all substrates. In general, the addition of ligands improves the chemoselectivity toward 1,2-diols but reduces the rate of the reaction. Except for stilbene, chemoselectivities of 78−97% were realized under optimized conditions. In the case of 1-phenyl-1-cyclohexene and *trans*-stilbene, we observed that the dihydroxylation is faster at pH 11.2 than at pH 10.4, with or without the presence of ligands. Enantioselectivities of 89−95% were obtained with $(DHQD)_2PHAL$ as the chiral ligand. Again these values are smaller than those of dihydroxylations using $K_3[Fe(CN)_6]$ as the oxidant (97−99.8% ee).

Dihydroxylation of Aliphatic Olefins. Previously we have shown that 1-octene reacts efficiently with OsO_4 in the presence of dioxygen. Initial tests with internal aliphatic olefins (*trans*-5-decene, 2-methyl-2-pentene, 1-methyl-1-cyclohexene, and 2,3-dimethyl-2-butene), however, were rather disappointing. At pH 10.4 in the presence of 3 mol % of DABCO as ligand, the corresponding 1,2-diols were obtained in only 13−53% yields (Table 4). The reason for these poor yields is probably the slow hydrolysis of the corresponding sterically hindered Os(VI) glycolates. On the basis of the positive effect of a more basic buffer medium on the dihydroxylation of 1-phenyl-1-cyclohexene, we proposed that sterically hindered olefins might react more efficiently at higher pH values. Indeed, the reaction of 2,3-dimethyl-2-butene is significantly improved at a more basic pH value with the yield increasing from 13% at pH 10.4 to 65% at pH 12.0 (Table 5).

Applying 2 mol % of $K_2[OsO_2(OH)_4]$ as catalyst, the yield and selectivity is nearly quantitative. In addition, other olefins which form hydrolysis-stable Os(VI) glycolate complexes gave increased product yields at pH 11.2−12.0. In all cases, good to excellent yields (78−95%) and chemoselectivities (80−98%) were obtained (Table 6).

Dihydroxylation of Functionalized Olefins. As shown above, unfunctionalized aromatic and aliphatic olefins proved to be good substrates for the dihydroxylation reaction in the presence of dioxygen. Clearly this new dihydroxylation procedure is of significant importance to synthetic organic chemists only, if various functional groups are tolerated. Hence, we were interested in the reaction of functionalized olefins. So far no dihydroxylations of functionalized olefins either in the presence of dioxygen or air have been reported. Initial tests with cinnamic as well as acrylic acid derivatives showed that these substrates react only very sluggishly.[27] However, as depicted in Table 7 other olefins such as allyl phenyl ether, allyl phenyl sulfide, allyltrimethylsilane, 1*H*,1*H*,2*H*-perfluoro-1-octene, and 2-vinyl-1,3-dioxolane all reacted with high chemoselectivities (84−97%) and sometimes good enantioselectivities (up to 85%).

The selective dihydroxylation of allyl phenyl sulfide is quite remarkable, as we observed no indication of oxidation of the sulfur atom. In agreement with results of nonfunctionalized terminal olefins, a pH of 10.4 provided the best results. The observed enantioselectivities are consistent with the results of Sharpless et al. that $(DHQD)_2AQN$ or $(DHQD)_2PYR$ ligands give better results for terminal olefins than $(DHQD)_2PHAL$.[28] This effect is especially obvious for allyltrimethylsilane (Table 7). The low enantioselectivity (12% *ee*) observed for the dihydroxylation of 1*H*,1*H*,2*H*-perfluoro-1-octene with $(DHQD)_2PHAL$ compared to the reaction of 1-octene (65% ee under similar conditions[21]) is surprising. Apart from electronic changes, the different solubilities of the two compounds might be responsible for this different behavior. However, previous work on the asymmetric dihydroxylation of halogenated olefins showed the opposite effect. With $(DHQD)_2PHAL$ the enantioselectivity of 3,3,3-trifluoropropene (63% ee) is higher than that of propene (35% ee).[29]

Discussion

At the start of this study it was unclear how general the osmium-catalyzed dihydroxylation using dioxygen as oxidant would be. The experimental results shown here demonstrate that a number of different olefin classes (1,1-disubstituted olefins, 1,2-disubstituted aliphatic olefins, terminal aliphatic olefins, tri- and tetrasubstituted olefins) and olefins with various functional groups (-SR; -OR; -F; -Cl; $-CH(OR)_2$; $-SiR_3$) react with good to excellent chemoselectivities. However, there are still substrates (stilbene, acrylic acid, cinnamic acid) which cause problems at present. In this respect it is interesting to note that reactions of aromatic olefins with an α-hydrogen atom occur in general with lower chemoselectivity compared to aliphatic olefins. We assumed that the lower chemoselectivity is the result of a subsequent oxidation of the benzylic position. To prove whether this benzylic oxidation is also catalyzed by OsO_4 or is a simple radical reaction with dioxygen, we performed oxidation reactions of stilbene-1,2-diol with dioxygen with and without the presence of $K_2[OsO_2(OH)_4]$ (Scheme 3).

After stirring hydrobenzoin (1,2-stilbenediol) for 24 h at 50 °C under 1 bar of dioxygen at pH 10.4 (buffered solution), no

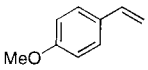
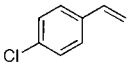
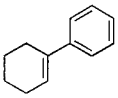
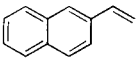
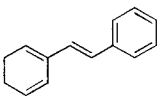
(26) Blaser, H.-U.; Pugin, B.; Spindler, F. In *Applied Homogeneous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; Vol. 2, pp 992−1009.

(27) In the case of acrylic acid, slow oxygen uptake indicates that some reaction takes place; however the products could not been isolated from the aqueous phase.

(28) Becker, H.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 448−451.

(29) (a) Vanhessche, K. P. M.; Sharpless, K. B. *Chem. Eur. J.* **1997**, *3*, 517−522. (b) Bennani, Y. L.; Vanhessche, K. P. M.; Sharpless, K. B. *Tetrahedron: Asymmetry* **1994**, *5*, 1473−1476.

Table 3. Dihydroxylation of Aromatic Olefins[a]

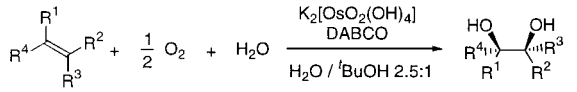
Entry	Olefin	Ligand	L/Os	[L] [mmol/l]	pH	Yield [%]	Selectivity [%]	*ee* [%]
1		-	-	-	10.4	43	57	-
2		-	-	-	11.2	39	60	-
3		DABCO	1:1	2	10.4	53	75	-
4		DABCO	3:1	6	10.4	43	78	-
5		DABCO	3:1	6	11.2	44	77	-
6		$(DHQD)_2PHAL$	1:1	2	10.4	49	74	89
7		$(DHQD)_2PHAL$	1:1	2	11.2	45	77	76
8		$(DHQD)_2PHAL$	1:1	2	13.0	12	55	20
9		$(DHQD)_2PHAL$	3:1	6	10.4	40	80	89
10		$(DHQD)_2PHAL$	3:1	6	11.2	38	78	88
11		DABCO	3:1	6	10.4	35	97	-
12		$(DHQD)_2PHAL$	3:1	6	10.4	35	97	92
13		DABCO	3:1	6	10.4	45	85	-
14		$(DHQD)_2PHAL$	3:1	6	10.4	48	85	95
15		-	-	-	10.4	76	84	-
16		-	-	-	11.2	75	77	-
17		$(DHQD)_2PHAL$	1:1	2	10.4	54	83	87
18		$(DHQD)_2PHAL$	1:1	2	11.2	82	85	90
19		$(DHQD)_2PHAL$	3:1	6	10.4	42	84	87
20		$(DHQD)_2PHAL$	3:1	6	11.2	80	85	90
21		$(DHQD)_2PHAL$	3:1	6	13.0	21	72	61
22		-	-	-	10.4	32	42	-
23		-	-	-	11.2	28	29	-
24		DABCO	1:1	2	10.4	47	56	-
25		DABCO	1:1	2	11.2	38	41	-
26		DABCO	3:1	6	10.4	56	75	-
27		DABCO	3:1	6	11.2	42	51	-
28		$(DHQD)_2PHAL$	1:1	2	10.4	46	78	93
29		$(DHQD)_2PHAL$	1:1	2	11.2	52	69	93
30		$(DHQD)_2PHAL$	3:1	6	10.4	55	76	95
31[b]		-	-	-	10.4	9	10	-
32[b]		DABCO	3:1	1.5	10.4	10	23	-
33[b]		DABCO	3:1	1.5	11.2	19	44	-
34[b]		DABCO	3:1	1.5	12.0	18	64	-
35[b]		$(DHQD)_2PHAL$	3:1	1.5	11.2	15	28	93
36[b]		$(DHQD)_2PHAL$	3:1	1.5	12.0	15	63	88
37[b,c]		$(DHQD)_2PHAL$	3:1	3	12.0	25	54	90
38[b]		$(DHQD)_2PHAL$	3:1	1.5	13.0	12	80	54

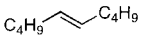
[a] Reaction conditions: 2 mmol of olefin, 1 mol % of $K_2[OsO_2(OH)_4]$, 50 °C, 1 bar ofo O_2, 25 mL of buffer solution, 10 mL of *t*-BuOH, 24 h. [b] 1 mmol of *trans*-stilbene, 15 mL of buffer solution, 20 mL of *t*-BuOH, 24 h. [c] 2 mol % of $K_2[OsO_2(OH)_4]$.

significant conversion of the diol was observed as shown by no dioxygen uptake. Similar reactions in the presence of 1 mol % of $K_2[OsO_2(OH)_4]$ revealed a total conversion of the diol after 24 h at 50 °C and pH 10.4, yielding mixtures of benzoic acid, benzaldehyde, and other oxygenated products. Thus, OsO_4 also catalyzes the oxidative cleavage of aromatic 1,2-diols. Again, this reaction is strongly pH dependent and is favored by two α-aryl substituents. Further studies of this reaction are currently underway.

With regard to the mechanism of the described dihydroxylation, we propose a catalytic cycle similar to the one presented by Sharpless et al. for the osmium-mediated dihydroxylation with $K_3[Fe(CN)_6]$ as the reoxidant (Scheme 4). There is obviously only a minor involvement of a second catalytic cycle as suggested for the dihydroxylation with NMO, with the intermediate Os(VI) glycolate being oxidized to a Os(VIII) species prior to hydrolysis.[30] Such a second cycle would lead to significantly lower enantioselectivities, as the attack of a second olefin molecule on the Os(VIII) glycolate occurs in the absence of chiral ligand. As outlined above, the observed enantioselectivities for the dihydroxylation with oxygen are lower but close to the data previously published by the Sharpless

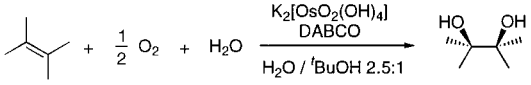
Table 4. Dihydroxylation of Aliphatic Olefins[a]



Olefin	Cat. [mol%]	Yield [%]	Sel. [%]
	2	27	89
	1	53	71
	1	26	n.d.
	1	13	31

[a] Reaction conditions: 2 mmol of olefin, DABCO/osmium = 3:1, 50 °C, 1 bar of O_2, 25 mL of buffer solution (pH 10.4), 10 mL of *t*-BuOH, 18 h.

Table 5. Dihydroxylation of 2,3-Dimethyl-2-butene at Different pH Values[a]



pH	cat. [mol %]	yield [%]	sel. [%]
10.8	1	23	31
11.2	1	51	81
12.0	1	65	88
13.0	1	41	69
12.0	2	94	99

[a] Reaction conditions: 2 mmol of 2,3-dimethyl-2-butene, ligand/osmium = 3:1, 50 °C, 1 bar of O_2, 25 mL of buffer solution, 10 mL of *t*-BuOH, 18 h.

group, despite the higher reaction temperature (50 °C vs 0 °C). This is an indication that the direct oxidation of the Os(VI) glycolate to an Os(VIII) glycolate is no major pathway under the described reaction conditions. To compare dioxygen with $K_3[Fe(CN)_6]$ more precisely, we performed the catalytic dihydroxylation of α-methylstyrene with both reoxidants at 50 °C at pH 10.7 in the presence of 1.5 mol % and 5 mol % of $(DHQD)_2PHAL$. The use of $K_3[Fe(CN)_6]$ gave an enantioselectivity of 87 and 88% ee, respectively. In the presence of dioxygen an ee of 80% (1.5 mol % of $(DHQD)_2PHAL$) and 85% (5 mol % of $(DHQD)_2PHAL$) was obtained. Further increase of the ligand concentration does not lead to the ceiling ee (88%) at this temperature. Therefore it appears that dioxygen is a lower selective oxidant compared to $K_3[Fe(CN)_6]$. Nevertheless the Os(VI) hydroxide complexes should be mainly oxidized by dioxygen, but not the intermediate Os(VI) glycolates.

With most substrates, differences in the stereoselective induction were observed compared to the use of $K_3[Fe(CN)_6]$ as terminal oxidant, but the ligand−olefin structure relationship is similar to previously reported results. However, we observed some interesting details in the present system: the enantioselectivity is strongly dependent on the pH value of the buffer system. The more basic the solution becomes the lower the obtained enantioselectivity is (Table 3, entries 6−10). We explain this behavior by a competition between hydroxide ions and the chiral hydrochinidine derivatives, both acting as ligands toward the central Os atom. Apparently, the reaction of olefin with nonchiral osmium hydroxide complexes is competitive to the reaction with osmium alkaloid complexes at a strong basic pH (>12).

Especially noteworthy is the retarding effect of the ligand observed for the dihydroxylation of aromatic olefins. We propose that for these olefins neither the reaction of the OsO_4−ligand complex with the olefin nor the hydrolysis of the Os(VI) glycolate is the rate-determining step of the catalytic cycle (Scheme 4). In agreement with the increased turnover frequency at higher oxygen pressure, the reoxidation of the Os(VI) hydroxy species is most likely the critical reaction step. Apparently this reoxidation is inhibited by ligands.

The significant influence of the pH between 9.5 and 12 on the catalyst productivity is explained by the formation of anionic Os(VI) hydroxide species and a faster hydrolysis of Os(VI) glycolates. In principle, more basic anionic Os(VI) hydroxide complexes should be more easily oxidized compared to neutral species.[31] The slow and nonselective dihydroxylation of tri-and tetrasubstituted olefins at pH 10.4 demonstrates that the hydrolysis step of the Os(VI) glycolate complexe is rate determining for this class of sterically hindered olefins. However, by simply making the reaction solution more basic, this hydrolysis becomes very efficient. For the future one would expect that the careful control of pH value will lead to efficient dihydroxylations of all kinds of sterically hindered olefins independent from the oxidant.

When the reactions proceed with high chemoselectivity, two molecules of diol are produced out of one molecule of dioxygen. Therefore, this method represents one of the rare cases of 100% atom economic oxidation reactions applying dioxygen as the oxidant.

Conclusion

The use of dioxygen in selective oxidation reactions for the synthesis of fine chemicals in an environmentally friendly way is an important challenge in catalysis. We have demonstrated that Os-catalyzed dihydroxylations of various olefins can be performed efficiently in the presence of dioxygen or air. Using α-methylstyrene as a model substrate, it is shown that in the presence of very small catalyst-to-substrate ratios (up to 1:4000) high yields of the corresponding 1,2-diol are possible at slightly elevated oxygen pressures. Even sterically hindered 1,2-di, tri-, and tetrasubstituted olefins are dihydroxylated, without the need for addition of stoichiometric amounts of a hydrolyzing agent such as methanesulfonamide. In the presence of chiral dihydroquinidine or dihydroquinine derivatives (Sharpless ligands), asymmetric dihydroxylations take place, albeit with lower enantioselectivities compared to those obtained under the Sharpless AD conditions.

Experimental Section

General. ^1H and ^{13}C NMR spectra were recorded on a Bruker ARX 400 spectrometer (^1H 400.1 MHz, ^{13}C 100.6 MHz). Chemical shifts (δ) are given in ppm and refer to residual solvent as internal standard. Gas chromatography was performed on a Hewlett-Packard HP 6890 chromatograph with a HP5 column. Mass spectra were recorded on a AMD 402/3 mass spectrometer. The products were purified on silica

(30) Wai, J. S. M.; Markó, I.; Svendsen, J. S.; Finn, M. G.; Jacobsen, E. N.; Sharpless, K. B. *J. Am. Chem. Soc.* **1989**, *111*, 1123−1125.

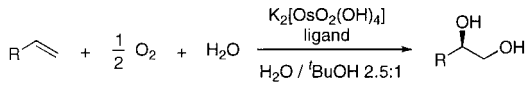
(31) Périchon, J.; Palous, S.; Buvet, R. *Bull. Soc. Chim. Fr.* **1963**, 982−988.

Table 6. Dihydroxylation of Aliphatic Olefins under Optimized pH Conditions[a]

Olefin	Ligand	pH	Cat. [mol%]	Yield [%]	Sel. [%]	*ee* [%]
C_4H_9 C_4H_9	DABCO	12.0	2	85	96	-
	$(DHQD)_2PHAL$	12.0	2	95	98	88
	DABCO	11.2	1	78	80	-
	$(DHQD)_2PHAL$	11.2	1	82	85	49
	DABCO	11.2	2	88	n.d.	-
	$(DHQD)_2PHAL$	11.2	2	88	n.d.	87

[a] Reaction conditions: 2 mmol of olefin, ligand/osmium = 3:1, 50 °C, 1 bar of O_2, 25 mL of buffer solution, 10 mL of *t*-BuOH, 18 h.

Table 7. Dihydroxylation of Functionalized Olefins[a]

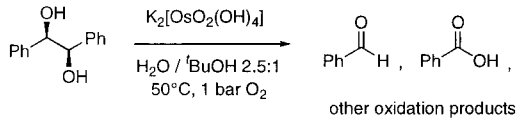


Olefin	Ligand	Yield [%]	Sel. [%]	*ee* [%]
	DABCO[b]	94	96	-
	$(DHQD)_2PHAL$	80	95	74
	$(DHQD)_2AQN$	57	97	88
	DABCO[b]	61	94	-
	$(DHQD)_2PHAL$	79	96	37
	$(DHQD)_2AQN$	67	92	63
Me_3Si	DABCO	72[c]	83	-
	$(DHQD)_2PHAL$	79[d]	89	15
	$(DHQD)_2AQN$	72[d]	84	12
	$(DHQD)_2PYR$	76[d]	88	79
C_6F_{13}	DABCO	53	84	-
	$(DHQD)_2PHAL$	45	82	12
	$(DHQD)_2AQN$	40	82	45
	$(DHQD)_2PYR$	45	87	67
	DABCO	59	97	-
	$(DHQD)_2PHAL$	63	86	23
	$(DHQD)_2AQN$	60	85	34
	$(DHQD)_2PYR$	53	68	41

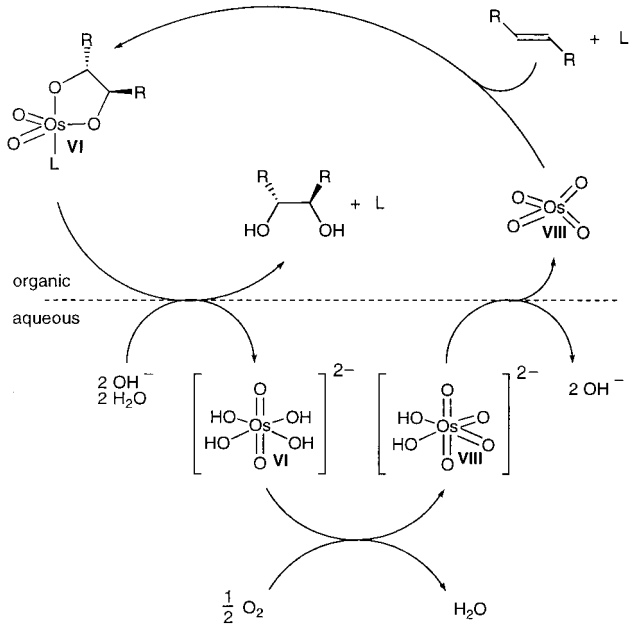
[a] Reaction conditions: 2 mmol of olefin, 50 °C, 1 bar of O_2, 25 mL of buffer solution (pH 10.4), 10 mL of *t*-BuOH, 18 h, 1 mol % of $K_2[OsO_2(OH)_4]$ for allyl phenyl ether, allyl phenyl sulfide, and allyltrimethylsilane, 2 mol % of $K_2[OsO_2(OH)_4]$ for 1*H*,1*H*,2*H*-perfluoro-1-octene and 2-vinyl-1,3-dioxolane, ligand/osmium = 3:1. [b] Ligand/osmium 1.5:1. [c] 14 h. [d] 7 h.

gel 60, 230−400 mesh (Merck). High-performance liquid chromatography was carried out using a Hewlett-Packard HP 1090 liquid chromatograph equipped with a DAD. Enantiomeric excess values were

Scheme 3. Osmium-Catalyzed C−C Cleavage of 1,2-Diphenyl-1,2-ethanediol



Scheme 4. Proposed Catalytic Cycle for the Dihydroxylation of Olefins with OsO_4 and Oxygen as the Terminal Oxidant



either determined by HPLC of the isolated diol or its bisbenzoate derivative. The retention time of the major HPLC peak is printed in bold. The absolute configurations of the products were either determined by comparison with original samples or are based on the mnemonic device established by Sharpless et al.[32]

Dihydroxylation of α-Methylstyrene under Atmospheric Oxygen Pressure (Typical Procedure). In a 100 mL Schlenk tube, 3.7 mg (0.01 mmol) of $K_2[OsO_2(OH)_4]$ and 23.4 mg (0.03 mmol) of $(DHQD)_2PHAL$ were dissolved in a mixture of 10 mL of *t*-BuOH and 25 mL of anaqueous buffer solution (pH 10.4).[33] The Schlenk tube was then purged with oxygen, and the biphasic mixture was warmed to 50 °C in an oil bath. Then α-methylstyrene (260 μL, 2 mmol) was added in one portion by a syringe and the tube connected to a graduated

(32) Kolb, H. C.; Andersson, P. G.; Sharpless, K. B. *J. Am. Chem. Soc.* **1994**, *116*, 1278−1291.

gas buret filled with oxygen. The reaction mixture was stirred vigorously with a magnetic stirring bar, and the reaction was followed by observing the oxygen uptake.

After 24 h, 22 mL (ca. 1 mmol) of oxygen was consumed.[34] A small amount of Na_2SO_3 was added and the mixture was cooled to room temperature under stirring. The mixture was then extracted twice with 20 mL portions of ethyl acetate. The combined organic layers were dried over $MgSO_4$ and submitted for GC analysis after addition of 100 μL of diethylene glycol di-*n*-butyl ether as an internal GC standard. For isolation of the product, the solvent was removed under reduced pressure and the crude diol purified by column chromatography (hexane/ethyl acetate 2:1) to give 257 mg (93%) of 2-phenyl-1,2-propanediol as a white solid. HPLC analysis of the pure diol showed an enantiomeric excess of 88%.

Dihydroxylation of 2-Vinyl-2,3-dioxolane. 2-Vinyl-2,3-dioxolane (200 μL, 2 mmol) was reacted with 14.7 mg (2 mol %) of $K_2[OsO_2(OH)_4]$ and 93.6 mg (6 mol %) of $(DHQD)_2PHAL$ as described above. After 18 h, 15 mL of oxygen was consumed. For workup, the reaction mixture was extracted once with 20 mL of ethyl acetate and the amount of unreacted olefin was determined by GC analysis of the organic layer with diethylene glycol di-*n*-butyl ether as an internal GC standard. The aqueous layer was concentrated under reduced pressure and the residue extracted with 25 mL of EtOH. After filtration, the solvent was evaporated and the resulting crude diol purified by column chromatography ($CHCl_3$/MeOH 6:1) to yield 169 mg (63%) of 2-(1,2-dihydroxyethyl)-1,3-dioxolane as a colorless oil. HPLC analysis of the bisbenzoate derivative gave an enantiomeric excess of 23%.

Dihydroxylation of α-Methylstyrene under Elevated Pressure. In a 200 mL steel autoclave (Roth GmbH), equipped with a magnetic stirrer and a glass inline, 0.1 mol % of $K_2[OsO_2(OH)_4]$ (1.0 mL of a freshly prepared 2 mmol/L solution in aqueous buffer) and 23.4 mg (1.5 mol %) of $(DHQD)_2PHAL$ were dissolved in a mixture of 25 mL of an aqueous buffer solution (pH 10.4) and 10 mL of *t*-BuOH. The autoclave was purged with oxygen and 260 μL (2 mmol) α-methylstyrene was added. Then the autoclave was closed, pressurized with oxygen, and heated to 50 °C. After 24 h, the reaction mixture was worked up as described above to yield 251 mg (91%) of 2-phenyl-1,2-propanediol (79% ee).

Physical Data for Diols: 2-Phenyl-1,2-propanediol. ^{1}H NMR ($CDCl_3$): δ = 1.50 (s, 3H), 2.39 (brs, 2H), 3.58 (d, J = 11.1 Hz, 1H), 3.74 (d, J = 11.1 Hz, 1H), 7.23−7.41 (m, 5H); ^{13}C NMR: δ = 26.0, 71.0, 74.8, 125.0, 127.1, 128.4, 144.9; MS (EI, 70 eV), *m*/*e*: 152 ([M]$^+$, 2), 135 (2), 121 (88), 105 (5), 91 (6), 77 (10), 51 (5), 43 (100), 31 (3); HPLC (diol): (*R*,*R*)-Whelk-O1, 2% EtOH in hexane, flow rate 1.0 mL/min, t_R = 14.4 (*S*), **16.7** (*R*).

1-Phenyl-1,2-ethanediol. ^{1}H NMR ($CDCl_3$): δ = 2.6 (s, 2H), 3.63 (dd, J = 8.2, 11.4 Hz, 1H), 3.72 (dd, J = 3.6, 11.4 Hz), 4.79 (dd, J = 3.6, 8.2 Hz, 1H), 7.28−7.34 (m, 5H); ^{13}C NMR: δ = 68.0, 74.7, 126.0, 128.0, 128.5, 140.4; MS (EI, 70 eV), *m*/*e*: 138 ([M]$^+$, 9), 121 (14), 107 (100), 79 (56), 77 (29), 51 (6), 31 (4); HPLC (diol): Daicel Chiralcel OB-H, 5% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = **12.5** (*R*), 16.2 (*S*).

1-(4-Methoxyphenyl)-1,2-ethanediol. ^{1}H NMR ($CDCl_3$): δ = 2.25 (brs, 2H), 3.60−3.72 (m, 2H), 3.78 (s, 3H), 4.75 (dd, J = 3.8, 8.1 Hz, 1H), 6.82−7.31 (m, 4H); ^{13}C NMR: δ = 54.3, 67.0, 73.3, 112.9, 126.3, 131.6, 158.4; MS (EI, 70 eV), *m*/*e*: 168 ([M]$^+$, 7), 138 (9), 137 (100), 77 (24); HPLC (diol): Daicel Chiralcel OB, 10% *i*PrOH in hexane, flow rate 2.0 mL/min, t_R = **13.6** (*R*), t_R = 16.7 (*S*).

1-(4-Chlorophenyl)-1,2-ethanediol. ^{1}H NMR ($CDCl_3$): δ = 2.49 (s, 2H), 3.56−3.73 (m, 2H), 4.77 (dd, J = 3.4, 8.3 Hz, 1H), 7.26−7.32 (m, 4H); ^{13}C NMR: δ = 68.3, 74.4, 127.9, 129.1, 134.2, 139.3; MS (EI, 70 eV), *m*/*e*: 172 ([M]$^+$, 8), 141 (100), 77 (93); HPLC (diol): Daicel Chiralcel OD-H, 3% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = **29.9** (*R*), t_R = 35.1 (*S*).

1-Phenyl-1,2-cyclohexanediol. ^{1}H NMR ($CDCl_3$): δ = 1.35−1.89 (m, 11H), 3.96 (dd, J = 4.7, 11.1 Hz, 1H), 7.21−7.53 (m, 5H); ^{13}C NMR: δ = 21.1, 24.3, 30.9, 38.5, 74.5, 75.7, 125.1, 127.0, 128.5, 146.3; MS (EI, 70 eV), *m*/*e*: 192 ([M]$^+$, 59), 174 (20), 145 (10), 133 (100), 120 (36), 107 (5), 105 (68), 91 (18), 77 (36), 55 (26); HPLC (diol): Whelk (25 cm × 0.46 cm i.d.), 10% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = 4.4 (*S*, *S*), t_R = **6.4** (*R*, *R*).

1-(2-Naphthyl)-1,2-ethanediol. ^{1}H NMR (d_6-DMSO): δ = 3.64 (t, J = 5.9 Hz, 2H), 4.80−4.84 (m, 1H), 4.88 (t, J = 5.9 Hz, 1H), 5.49 (d, J = 4.2 Hz, 1H), 7.58−7.98 (m, 7H); ^{13}C NMR: δ = 68.4, 75.0, 120.0, 125.7, 126.1, 126.6, 127.0, 128.3, 128.8, 133.4, 133.9, 142.2; MS (EI, 70 eV), *m*/*e*: 188 ([M]$^+$, 5), 157 (100), 129 (88), 128 (37), 127 (22), 31 (6); HPLC (diol): Kromasil KR100-5CHI-TBB, 3% *i*PrOH in hexane, flow rate 0.3 mL/min, t_R = 50.0 (*S*), t_R = **53** (*R*).

1,2-Diphenyl-1,2-ethanediol. ^{1}H NMR ($CDCl_3$): δ = 2.73 (brs, 2H), 4.69 (s, 2H), 7.09−7.22 (m, 10H); ^{13}C NMR: δ = 79.1, 126.9, 127.9, 128.1, 139.8; MS (EI, 70 eV), *m*/*e*: 214 ([M]$^+$, 1), 197 (14), 108 (100), 107 (89), 79 (78), 77 (40), 51 (11); HPLC (diol): Daicel Chiralcel OB-H, 10% EtOH in hexane, flow rate 1.0 mL/min, t_R = **8.0** (*R*,*R*), 10.1 (*S*,*S*).

5,6-Decanediol. ^{1}H NMR ($CDCl_3$): δ = 0.89 (t, J = 7.2 Hz, 6H), 1.28−1.50 (m, 12H), 2.12 (s, 2H), 3.37−3.39 (m, 2H); ^{13}C NMR: δ = 14.0, 22.7, 27.8, 33.3, 74.5; MS (CI, isobutane), *m*/*e*: 175 ([M + H]$^+$, 2), 157 ([M − OH]$^+$, 100), 139 (15), 117 (2), 97 (5), 87 (12), 86 (11), 83 (14), 69 (19); HPLC (bisbenzoate): Daicel Chiralcel OD-H, 0.2% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = 6.0 (*S*,*S*), t_R = **7.3** (*R*,*R*).

1-Methyl-1,2-cyclohexanediol. ^{1}H NMR ($CDCl_3$): δ = 1.18−1.78 (m, 11H), 1.96 (brs, 2H), 3.37 (dd, J = 3.7, 9.1 Hz, 1H); ^{13}C NMR: δ = 21.5, 23.1, 26.5, 30.4, 36.8, 71.5, 74.8; MS (EI, 70 eV), *m*/*e*: 130 ([M]$^+$, 12), 112 (19), 97 (24), 83 (12), 71 (100), 58 (41), 43 (76); HPLC (bisbenzoate): Daicel Chiralcel OD-H, 1% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = 11.5 (1*R*, 2*S*), t_R = **13.1** (1*S*,2*R*).

2-Methyl-2,3-pentanediol. ^{1}H NMR ($CDCl_3$): δ = 0.98 (t, J = 7.3 Hz, 3H), 1.09 (s, 3H), 1.14 (s, 3H), 1.20−1.33 (m, 1H), 1.42−1.53 (m, 1H), 3.23 (dd, J = 2.2, 10.5 Hz, 1H), 3.34 (brs, 2H); ^{13}C NMR: δ = 11.3, 22.9, 24.5, 26.4, 73.3, 80.2; MS (CI, isobutane), *m*/*e*: 119 ([M + H]$^+$, 2), 101 ([M − OH]$^+$, 100), 83 (11), 71 (12), 60 (7); HPLC (bisbenzoate): Daicel Chiralcel OD-H, 0.3% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = 11.5 (*S*, *S*), t_R = **13.0** (*R*,*R*).

2,3-Dimethyl-2,3-butanediol. ^{1}H NMR ($CDCl_3$): δ = 1.21 (s, 12 H), 2.04 (s, 2H); ^{13}C NMR: δ = 24.8, 75.0; MS (EI, 70 eV), *m*/*e*: 85 ([M − H_2O − CH_3]$^+$, 22), 59 (100), 57 (62), 43 (54).

3-Phenoxy-1,2-propanediol. ^{1}H NMR ($CDCl_3$): δ = 2.10 (brs, 2H), 3.74 (dd, J = 5.2, 11.3 Hz, 1H), 3.83, (dd, J = 3.7, 11.3 Hz, 1H), 3.99−4.12 (m, 3H), 6.85−7.29 (m, 5H); ^{13}C NMR: δ = 63.7, 69.1, 70.3, 114.5, 121.3, 129.6, 158.3; MS (EI, 70 eV), *m*/*e*: 168 ([M]$^+$, 27), 119 (9), 94 (100), 77 (17); HPLC (diol): Daicel Chiralcel OD-H, 20% *i*PrOH in hexane, flow rate 1.0 mL/min, t_R = 6.7 (*R*), t_R = **11.9** (*S*).

(2,3-Dihydroxypropyl) Phenyl Sulfide. ^{1}H NMR ($CDCl_3$): δ = 2.28 (brs, 2H), 2.92 (dd, J = 8.1, 13.9 Hz, 1H), 3.04 (dd, J = 4.6, 13.9 Hz, 1H), 3.51 (dd, J = 5.6, 11.1 Hz, 1H), 3.67−3.74 (m, 2H), 7.16−7.34 (m, 5H); ^{13}C NMR: δ = 37.8, 65.1, 69.7, 126.8, 129.1, 130.1, 134.8; MS (EI, 70 eV), *m*/*e*: 184 ([M]$^+$, 46), 152 (7), 135 (32), 123 (44), 110 (100), 91 (24), 65 (18), 45 (30); HPLC (diol): Daicel Chiralcel OD-H, 5% EtOH in hexane, flow rate 1.0 mL/min, t_R = **14.2** (*S*), t_R = 16.0 (*R*).

3-(Trimethylsilyl)-1,2-propanediol. ^{1}H NMR ($CDCl_3$): δ = 0.01 (s, 9H), 0.65 (dd, J = 4.4, 14.5 Hz, 1H), 0.76 (dd, J = 8.1, 14.5 Hz, 1H), 3.28 (dd, J = 8.4, 11.0 Hz, 1H), 3.40−3.58 (m, 2H), 3.68−3.86 (m, 2H); ^{13}C NMR: δ = −0.9, 21.5, 68.9, 70.3; MS (CI, isobutane), *m*/*e*: 149 ([M + H]$^+$, 1), 131 ([M − OH]$^+$, 77), 115 (11), 91 (15), 75 ([M − $Si(CH_3)_3$)]$^+$, 100), 73 (21); HPLC (bisbenzoate): Daicel Chiralcel OD-H, 0.2% EtOH in hexane, flow rate 1.0 mL/min, t_R = **9.3** (*S*), t_R = 10.5 (*R*).

1*H*,1*H*,2*H*-Perfluorooctane-1,2-diol. ^{1}H NMR (d_6-DMSO): δ = 3.74 (m, 1H), 3.93 (m, 1H), 4.30 (m, 1H), 5.24 (s, 1H), 6.49 (s, 1H); ^{13}C NMR: δ = 60.2, 76.9, 110.2, 110.9, 112.9, 115.3, 116.8, 119.4; MS (CI, isobutane), *m*/*e*: 381 ([M + H]$^+$, 100), 363 ([M − OH]$^+$, 24), 330 (2), 273 (1), 154 (7), 111 (11); HPLC (bisbenzoate): Daicel

(33) The different buffer solutions were prepared as follows: 34.0 g of potassium dihydrogen phosphate were dissolved in 500 mL of water and the pH of the solution was then adjusted to the desired value by addition of the required amount of 2 N NaOH.

(34) When reactions are of low selectivity, a greater amount of oxygen is consumed.

Chiralcel OD-H, 0.15% EtOH in hexane, flow rate 1.0 mL/min, t_R = **7.1** (*S*), t_R = 8.0 (*R*).

2-(1,2-Dihydroxyethyl)-1,3-dioxolane. ^{1}H NMR ($CDCl_3$): δ = 2.86 (s, 2H), 3.67−3.75 (m, 3H), 3.86−4.02 (m, 4H), 4.88 (d, J = 3.4 Hz, 1H); ^{13}C NMR: δ = 62.6, 65.1, 65.3, 71.8, 103.7; MS (EI, 70 eV), *m*/*e*: 117 ([M − OH]$^+$, 10), 73 (100), 45 (41), 31 (11), 29 (11); HPLC (bisbenzoate): Daicel Chiralpak AD, 5% EtOH in hexane, flow rate 1.0 mL/min, t_R = 22.0 (*R*), t_R = **30.4** (*S*).

Acknowledgment. Dedicated to Prof. Dr. Günther Wilke on the occasion of his 75th birthday. The authors thank Mrs. I. Stahr for excellent technical support and Dr. C. Fischer for her continuous help with the HPLC analysis. Dr. H. Hugl, Dr. C. Militzer, and Dr. M. Eckert (Bayer AG) are thanked for general discussions. We also thank Dr. M. Hateley for help with this manuscript and Prof. Dr. K. B. Sharpless for helpful comments. Financial support from Bayer AG and the Ministry of Education, Science and Cultural Affairs of Mecklenburg-Vorpommern is gratefully acknowledged.

JA000802U