J|A|C|S
COMMUNICATIONS

Published on Web 04/10/2009

Iron-Catalyzed Asymmetric Aerobic Oxidation: Oxidative Coupling of 2-Naphthols

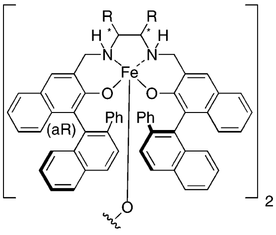
Hiromichi Egami and Tsutomu Katsuki*

Department of Chemistry, Faculty of Science, Graduate School, Kyushu University, Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

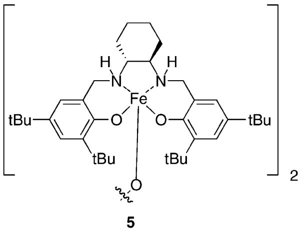
Received February 23, 2009; E-mail: katsuscc@chem.kyushu-univ.jp

Asymmetric oxidation is a versatile tool for the generation of chiral scaffolds in organic synthesis, and various metal complexes have been used as catalysts of these types of reactions. The utility of oxidation is mainly measured by several factors, including selectivity and ecological sustainability of the oxidation and the availability of the oxidant and catalyst. Among various oxidants, molecular oxygen in air is ubiquitous, available at no cost and easy-to-handle.[1] On the other hand, iron ions are abundant and inexpensive, they exhibit redox catalysis, and many oxidizing enzymes contain iron ions in their active site.

Thus, much effort has been directed toward the development of ecologically sustainable asymmetric oxidation using iron complexes as catalysts.[2] Jacobsen et al. reported on an iron-catalyzed asymmetric epoxidation using hydrogen peroxide as the oxidant, albeit with low enantioselectivity.[3] Bolm and Legros achieved highly enantioselective oxidation of sulfides using an Fe-Schiff base complex/H_2O_2 system.[4] More recently, we found that the Fe(salan) complex is an efficient catalyst for the asymmetric oxidation of sulfides using H_2O_2 in water.[5] Beller and co-workers reported on the enantioselective epoxidation of stilbene derivatives using H_2O_2.[6] Que and co-workers also achieved asymmetric dihydroxylation of olefins using H_2O_2.[7] Considering the above advantages of air as an oxidant, iron-mediated aerobic oxidation should be ideal. Xu et al. reported an iron-catalyzed asymmetric epoxidation using a combination of molecular oxygen and sacrificial aldehyde (Mukaiyama condition).[8] To the best of our knowledge, however, no iron-catalyzed asymmetric oxidation using molecular oxygen in air as the oxidant and in the absence of any additives has been reported.[9] To enhance the oxidation catalysis of an iron complex, its oxidation potential should be reduced. Coordination of a donating ligand should reduce the oxidation potential of the metal complex and facilitate aerobic oxidation. The salan ligand has two donating amino groups[10,11] and amino protons that might participate in hydrogen bonding with the substrate and regulate the transition state structure. Thus, we were intrigued by the asymmetric aerobic oxidation catalysis of the Fe(salan) complex.[10] Herein, we disclose the asymmetric aerobic oxidative coupling of 2-naphthol derivatives using Fe(salan) complexes.[12−15]

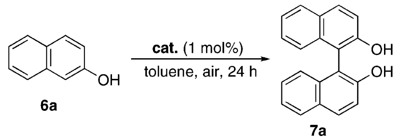


1: (aR, R), R = -$(CH_2)_4$-
2: (aR, S), R = -$(CH_2)_4$-
3: (aR, R), R = Ph
4: (aR, S), R = Ph



5

Table 1. Asymmetric Oxidative Coupling of 2-Naphthol[a]



entry	cat.	*T* (°C)	yield[b] (%)	ee[c] (%)	config. [d]
1	**1**	30	n.r.	-	
2	**2**	30	trace	-	
3	**3**	30	18	57	*S*
4	**4**	30	trace	-	
5	**5**	30	n.r.	-	
6	**3**	40	28	58	*S*
7	**3**	60	58	58	*S*
8	**1**	60	32	62	*S*
9	**2**	60	31	65	*R*
10[e]	**2**	60	87	64	*R*

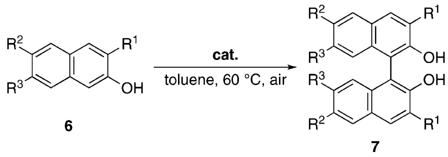
[a] The reactions were carried out in toluene with catalyst (1 mol%) on a 0.5 mmol scale under aerobic conditions, unless otherwise mentioned. [b] Determined by ^1H NMR analysis using pentamethylbenzene as the internal standard. [c] Determined by HPLC analysis on a chiral stationary phase column (Daisel Chiralcel AS-H). [d] Determined by chiroptical comparison with the literature value. [e] Run with 4 mol% of **2** for 72 h.

We first examined the reaction using various Fe(salan) complexes (**1**−**5**) as the catalyst in air at 30 °C (Table 1). While most complexes showed no or poor oxidation catalysis, only complex **3** bearing a diphenylethylenediamine unit exhibited moderate oxidation catalysis (entries 1−5). The reaction also proceeded at 40 or 60 °C without reducing the ee of the product (entries 3, 6, and 7). Thus, the reactions with other complexes were examined at 60 °C, and it was found that complexes **1** and **2** also catalyzed the oxidation. Furthermore, complex **2** showed to have one the best enantioselectivities, albeit with moderate yield (entries 7−9). The reaction with 4 mol% of catalyst **2** gave an acceptable yield without eroding the enantioselectivity (entry 10).

Under the optimized conditions, oxidative couplings of several other 2-naphthol derivatives were examined (Table 2). Moderate enantioselectivities were obtained in the reaction of 6-substituted 2-naphthols, irrespective of the electronic natures of the substituents (entries 2 and 3). The reaction of 7-substituted naphthol showed a higher enantioselectivity (entry 4). On the other hand, the reaction of 3-substituted naphthols with complex **2** showed only modest enantioselectivity; however the products, 3,3′-substituted binaphthols, are of high value as chiral ligands.[16] For example, the reaction of 3-methyl-2-naphthol **6e** with **2** gave only 16% ee (entry 5). To our delight, however, **3** was found to be a better catalyst for the coupling of this class of substrates. The oxidation of **6e** with **3** showed a good enantioselectivity of 77% ee (entry 6). Moreover, the reactions of naphthols bearing a bulkier substituent at the 3 position proceeded with high enantioselectivities greater than 90% ee (entries 7−14).[17]

10.1021/ja901391u CCC: $40.75

Table 2. Asymmetric Oxidative Coupling of Various 2-Naphthols[a]



entry	cat.	R^1	R^2	R^3		yield (%)	ee[b] (%)
1	**2**	H	H	H	**a**	84	64 (*R*)[c]
2	**2**	H	Br	H	**b**	93	47 (*R*)[c]
3[d]	**2**	H	MeO	H	**c**	79	56 (*R*)[c]
4[e]	**2**	H	H	MeO	**d**	86	74 (*R*)[c]
5	**2**	Me	H	H	**e**	64	16 (*R*)[c]
6[f]	**3**	Me	H	H	**e**	89	77 (*R*)[c]
7[d]	**3**	Ph	H	H	**f**	94	93 (*R*)[c]
8[d]	**3**	4-Ph-C_6H_4	H	H	**g**	91	92 (*R*)[c]
9[d]	**3**	2-naphthyl	H	H	**h**	91	94 (*R*)[c]
10[e]	**3**	PhC≡C	H	H	**i**	91	96
11[d]	**3**	TMSC≡C	H	H	**j**	69	97
12[g]	**3**	Cl	H	H	**k**	82	94 (*R*)[c]
13[g]	**3**	Br	H	H	**l**	86	94 (*R*)[c]
14[g]	**3**	I	H	H	**m**	77	96 (*R*)[c]
15	**3**	CO_2Me	H	H	**n**	n.r.	-

[a] The reactions were carried out in toluene with **2** (4 mol%) for 72 h on the 0.5 mmol scale under aerobic conditions, unless otherwise mentioned. [b] Determined by HPLC analysis on a chiral stationary phase column. [c] Determined by comparison of the chiroptical data with the literature value. [d] Run for 24 h. [e] Run for 48 h. [f] Run for 36 h at 40 °C. [g] Run for 96 h.

It is of note that compounds **7k**−**m** can be converted smoothly to various 3,3′-disubstituted binaphthols via a cross coupling reaction. These binaphthols were recrystallized to optical purity.[18] However, the coupling reaction of **6n** was sluggish, probably because of a chelate formation (entry 15).[14]

In summary, we were able to determine that Fe(salan) complexes are efficient catalysts for aerobic oxidative coupling of naphthols, especially of 3-substituted naphthols. This oxidative coupling provides a general and eco-friendly method for the synthesis of chiral 3,3′-disubstituted binaphthols, which have been widely used as chiral ligands or as organocatalysts.[16] To the best of our knowledge, this is the first report on iron-catalyzed asymmetric aerobic oxidation without the use of additives. Further study on the mechanism of this aerobic oxidative coupling is in progress.

Acknowledgment. Financial support from Specially Promoted Research 18002011 and the Global COE Program, "Science for Future Molecular Systems" from the Ministry of Education, Science, and Culture, Japan is gratefully acknowledged. H.E. is grateful for the JSPS Research Fellowships for Young Scientists.

Supporting Information Available: Experimental procedures, spectra data for binaphthols, and HPLC conditions. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Reviews on oxidation using hydrogen peroxide or molecular oxygen. (a) Bäckvall, J.-E., Ed. *Modern Oxidation Methods*; Wiley-VCH: Weinheim, 2004. (b) Noyori, R.; Aoki, M.; Sato, K. *Chem. Commun.* **2003**, *197*, 1977–1986. (c) Lane, B. S.; Burgess, K. *Chem. Rev.* **2003**, *103*, 2457–2473. (d) Beller, M. *Adv. Synth. Catal.* **2004**, *346*, 107–108. (e) ten Brink, G.-J.; Arends, I. W. C. E.; Sheldon, R. A. *Chem. Rev.* **2004**, *104*, 4105–4123. (f) Irie, R.; Katsuki, T. *Chem. Records* **2004**, *4*, 96–109. (g) Kaczorowaka, K.; Kolarska, Z.; Mitka, K.; Kowalski, P. *Tetrahedron* **2005**, *61*, 8315–8327.

(2) Reviews on iron-catalyzed reactions. (a) Bolm, C.; Legros, J.; Paih, J. L.; Zani, L. *Chem. Rev.* **2004**, *104*, 6217–6254. (b) Correa, A.; Mancheño, O. G.; Bolm, C. *Chem. Soc. Rev.* **2008**, *37*, 1108–1117. (c) Gaillard, S.; Renaud, J.-L. *ChemSusChem* **2008**, *1*, 505–509. (d) Enthaler, S.; Junge, K.; Beller, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 3317–3321.

(3) Francis, M. B.; Jacobsen, E. N. *Angew. Chem., Int. Ed.* **1999**, *38*, 937–941.

(4) (a) Legros, J.; Bolm, C. *Angew. Chem., Int. Ed.* **2003**, *42*, 5487–5489. (b) Legros, J.; Bolm, C. *Angew. Chem., Int. Ed.* **2004**, *43*, 4225–4228. (c) Legros, J.; Bolm, C. *Chem.—Eur. J.* **2005**, *11*, 1086–1092.

(5) (a) Egami, H.; Katsuki, T. *J. Am. Chem. Soc.* **2007**, *129*, 8940–8941. (b) Egami, H.; Katsuki, T. *Synlett* **2008**, 1543–1546.

(6) (a) Gelalcha, F. G.; Bitterlich, B.; Anilkumar, G.; Tse, M. K.; Beller, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 7293–7296. (b) Gelalcha, F. G.; Anilkumar, G.; Tse, M. K.; Brückner, A.; Beller, M. *Chem.—Eur. J.* **2008**, *14*, 7687–7698.

(7) (a) Costas, M.; Tipton, A. K.; Chen, K.; Jo, D.-H.; Que, L., Jr. *J. Am. Chem. Soc.* **2001**, *123*, 6722–6723. (b) Suzuki, K.; Oldenburg, P. D.; Que, L., Jr. *Angew. Chem., Int. Ed.* **2008**, *47*, 1887–1889.

(8) (a) Cheng, Q. F.; Xu, X. Y.; Ma, W. X.; Yang, S. J.; You, T. P. *Chin. Chem. Lett.* **2005**, *16*, 1467–1470. (b) Mukaiyama, T.; Yamada, T. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 17–35.

(9) For other selected reports of iron catalyzed asymmetric oxidation. (a) Duboc-Toia, C.; Ménage, S.; Lambeaux, C.; Fontecave, M. *Tetrahedron Lett.* **1997**, *38*, 3727–3730. (b) Mekmouche, Y.; Hummel, H.; Ho, R. Y. N.; Que, L., Jr; Schünemann, V.; Thomas, F.; Trautwein, A. X.; Lebrun, C.; Gorgy, K.; Leprêtre, J.-C.; Collomb, M.-N.; Deronzier, A.; Fontecave, M.; Ménage, S *Chem.—Eur. J.* **2002**, *8*, 1196–1202. (c) Bryliakov, K. P.; Talsi, E. P. *Angew. Chem., Int. Ed.* **2004**, *43*, 5228–5230. (d) Bryliakov, K. P.; Talsi, E. P. *Chem.—Eur. J.* **2007**, *13*, 8045–8050. (e) Nakanishi, M.; Salit, A.-F.; Bolm, C. *Adv. Synth. Catal.* **2008**, *350*, 1835–1840. (f) Yeung, H.-L.; Sham, K.-C.; Tsang, C.-S.; Lau, T.-C.; Knowg, H.-L. *Chem. Commun.* **2008**, 3801–3803.

(10) The oxidation of a Fe(III)(salan) complex takes places at a low oxidation potential of +0.55 V (vs Fc^+/Fc), and the salan complex is easily oxidized by ca. 0.30 V, as compared with the Fe(salen) complex. (a) Glaser, T.; Pawelke, R. H.; Heidemeier, M. *Z. Anorg. Allg. Chem.* **2003**, *629*, 2274–2281. (b) Strautmann, J. H.; George, S. D.; Bothe, E.; Bill, E.; Weyhermüller, T.; Stammier, A.; Bögge, H.; Glaser, T. *Inorg. Chem.* **2008**, *47*, 6804–6824.

(11) Fe(salen) complexes, which has similar structures to Fe(salan) complexes **1** or **3** did not catalyze the oxidative coupling of 2-naphthol under the present conditions.

(12) For the previous examples of iron-catalyzed oxidative coupling, see:(a) Toda, F.; Tanaka, K.; Iwata, S. *J. Org. Chem.* **1989**, *54*, 3007–3009. (b) Armengol, E.; Corma, A.; Garcia, H.; Primo, J. *Eur. J. Org. Chem.* **1999**, *191*, 5–1920. (c) Bhor, M. D.; Nandurkar, N. S.; Bhanushali, M. J; Bhanage, B. M. *Catal. Lett.* **2006**, *112*, 45–50. (d) Wang, K.; Lü, M.; Zhu, A. Y. X.; Wang, Q. *J. Org. Chem.* **2009**, *74*, 935–938.

(13) For a ruthenium catalyzed asymmetric aerobic oxidative coupling. Irie, R.; Masutani, K.; Katsuki, T. *Synlett* **2000**, *143*, 3–1436.

(14) Selected reports on copper catalyzed reactions. (a) Smrcina, M.; Poláková, J.; Vyskocil, S.; Kocovsky, P. *J. Org. Chem.* **1993**, *58*, 4534–4538. (b) Nakajima, M.; Miyoshi, I.; Kanayama, K.; Hashimoto, S.; Noji, M.; Koga, K. *J. Org. Chem.* **1999**, *64*, 2264–2271. (c) Li, X.; Yang, J.; Kozlowski, M. C. *Org. Lett.* **2001**, *3*, 1137–1140. (d) Li, X.; Hewgley, J. B.; Mulrooney, C. A.; Yang, J.; Kozlowski, M. C. *J. Org. Chem.* **2003**, *68*, 5500–5511. (e) Temma, T.; Hatano, B.; Habaue, S. *Tetrahedron* **2006**, *62*, 8559–8563. (f) Hewgley, J. B.; Stahl, S. S.; Kozlowski, M. C. *J. Am. Chem. Soc.* **2008**, *130*, 12232–12233.

(15) Selected reports on vanadium catalyzed reactions. (a) Chu, C.-Y.; Hwang, D.-R.; Wang, S.-K.; Uang, B.-J. *Chem. Commun.* **2001**, 980–981. (b) Barhate, N. B.; Chen, C.-T. *Org. Lett.* **2002**, *4*, 2529–2532. (c) Tada, M.; Taniike, T.; Kantam, L. M.; Iwasawa, Y. *Chem. Commun.* **2004**, 2542–2543. (d) Guo, Q.-X.; Wu, Z.-J.; Luo, Z.-B.; Liu, Q.-Z.; Ye, J.-L.; Luo, S.-W.; Cun, L.-F.; Gong, L.-Z. *J. Am. Chem. Soc.* **2007**, *129*, 13927–13938. (e) Takizawa, S.; Katayama, T.; Somei, H.; Asano, Y.; Yoshida, T.; Kameyama, C.; Rajesh, D.; Onitsuka, K.; Suzuki, T.; Mikami, M.; Yamataka, H.; Jayaprakash, D.; Sasai, H. *Tetrahedron* **2008**, *64*, 3361–3371.

(16) For the catalysts possessing a chiral 3,3′-disubstituted binaphthyl scaffold, see:(a) Connon, S. J. *Angew. Chem., Int. Ed.* **2006**, *45*, 3909–3912. (b) Akiyama, T. *Chem. Rev.* **2007**, *107*, 5744–5758.

(17) (b) To the best of our knowledge, no highly enantioselective method for the oxidative coupling of 3-substituted naphthols, except the ones bearing a precoordinating group such as an ester, ketone, or phosphine oxide group, has been reported. For examples of highly selective coupling of such precoordinating substrates, see: ref 14b,c,d.

(18) See the Supporting Information.

JA901391U