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Ligand and pH Influence on Manganese-Mediated Peracetic Acid Epoxidation of Terminal Olefins

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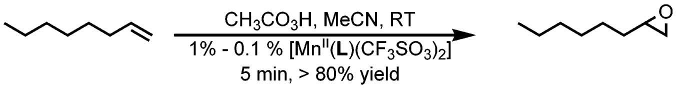
ABSTRACT



Nineteen Mn^{II} complexes were screened for the catalytic epoxidation of terminal olefins using peracetic acid. Few of these complexes are efficient catalysts at pH < 2, but many are effective at 1 mol % catalyst loading at pH 4. With 0.1 mol % loading, four complexes epoxidize 1-octene in ∼80% yield in 5 min. The relative reactivity of the catalysts toward different olefins was probed using a multicomponent intermolecular competition reaction.

Metal-catalyzed oxygenations of organic substrates are a widely used and studied class of reactions.[1] The development of catalytic epoxidation agents that are rapid, selective, scalable, and inexpensive with a wide substrate scope remains an important goal. Terminal olefins are a particularly challenging class of substrate to epoxidize,[2−9] yet the resulting 1,2-epoxides are extremely versatile starting materials for synthesizing more complicated molecules.[10]

We recently reported a monomeric manganous complex, $[Mn^{II}(\boldsymbol{R,R}\textbf{-mcp})(CF_3SO_3)_2]$, and a dimeric ferric complex, $[(Fe^{III}(\textbf{phen})_2)_2(\mu\text{-}O)(H_2O)_2](ClO_4)_4$, that are capable of rapidly catalyzing the epoxidation of terminal olefins using peracetic acid with 400−1000 turnovers within 5 min.[2,3] The reactivity of $[(Fe^{III}(\textbf{phen})_2)_2(\mu\text{-}O)(H_2O)_2](ClO_4)_4$ was found to be significantly dependent on the pH of the reaction solution, requiring a pH ≤ 2 for greatest activity.[3] By contrast, $[Mn^{II}(\boldsymbol{R,R}\textbf{-mcp})(CF_3SO_3)_2]$ exhibited activity that was effectively invariant to the pH under the conditions examined previously. To elucidate the pH effect on the reactivity of manganese catalysts and determine the role of the ligand on catalytic activity, we have screened a wide array of $[Mn^{II}(\mathbf{L})(CF_3SO_3)_2]$ complexes for their ability to epoxidize terminal olefins with commercial peracetic acid ($\mathbf{PAA_C}$, 1% H_2SO_4, pH ∼ 1) or peracetic acid prepared with strongly acidic resins ($\mathbf{PAA_R}$, pH ∼ 4).[11,12] Ligands were chosen to highlight the influence of the following properties on the catalytic activity of the Mn^{II} complex: oxidative stability, coordination mode, and thermodynamic stability (Figure 1). We have found that most manganous complexes of neutral polyamine ligands show a significant increase in epoxidation reactivity under less acidic conditions with peracetic acid if the ligation of the manganese center is appropriate.

The complexes were initially screened for their ability to epoxidize 1-octene at 1 mol % loading in 5 min using

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(11) Hawkinson, A. T.; Schmitz, W. R. (E.I. du Pont de Nemours & Co.). US 2910504, 1959.

(12) $\mathbf{PAA_R}$ is generated by stirring 50% H_2O_2 with 10 equiv of CH_3CO_2H and Amberlite IR-120 resin for 12 h at 25 °C. These solutions typically have <1% residual H_2O_2.

10.1021/ol048846l CCC: $27.50

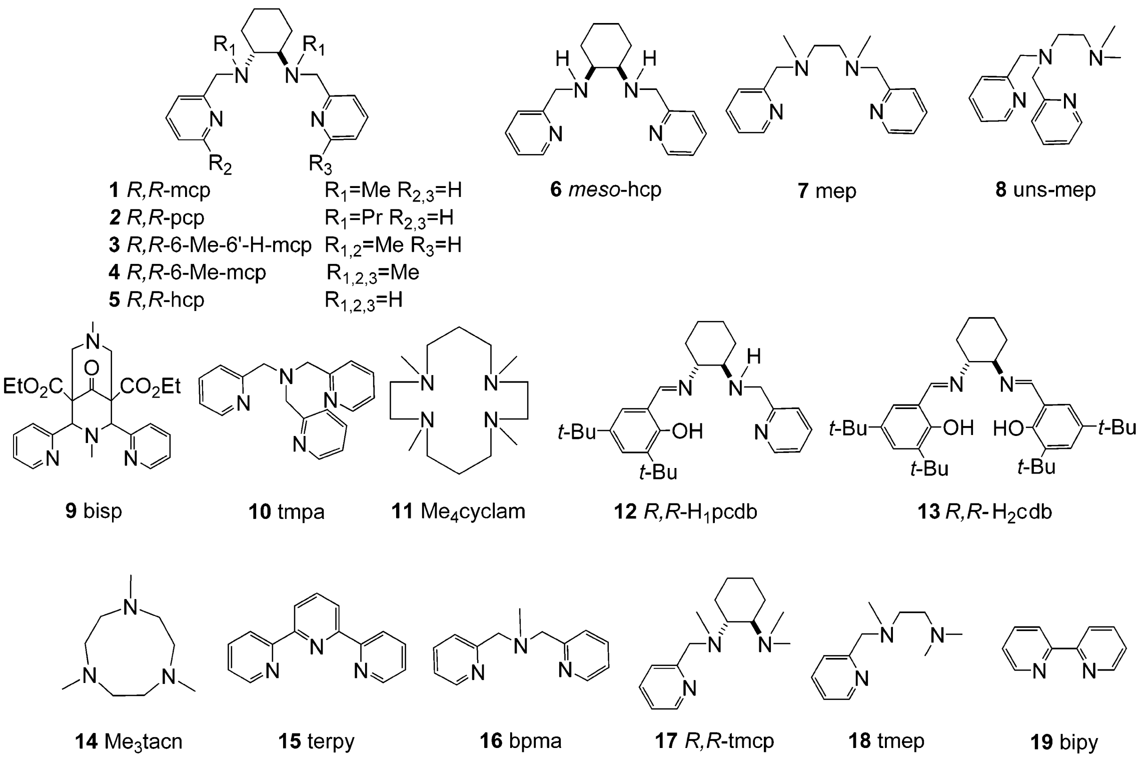

Figure 1. Ligands used in this study.

PAA_C.[13,14] The presence of strong acid in solution appears to attenuate the catalytic reactivity for the majority of complexes due to decomposition of the complex into protonated ligand and free Mn^{II} (Table 1). Simple Mn^{II} salts are ineffective catalysts for terminal olefin epoxidation with **PAA_C** under these conditions, although $Mn^{II}SO_4$ has been shown to be an effective epoxidation catalyst for electron-rich olefins with peroxycarbonate under basic conditions.[15] Only $[Mn^{II}($***R,R*-mcp**$)]^{2+}$, $[Mn^{II}($**bisp**$)]^{2+}$, and $[Mn^{II}($**Me_3-tacn**$)]^{2+}$ (Table 1, entries 1, 9, 14) show significant catalytic activity with **PAA_C**. These highly predisposed, neutral ligands allow the manganese center to accommodate at least two exogenous ligands in a cis fashion, and they create thermodynamically and kinetically stable complexes, which are more resistant to metal decomplexation. Both $[Mn^{II}($***R,R*-mcp**$)]^{2+}$ and $[Mn^{II}($**Me_3-tacn**$)]^{2+}$ have been previously reported to be capable of epoxidation at less than 1 mol % loadings.[2,16]

When **PAA_R**[11] is used as the oxidant, 14 of the 19 complexes provide $>90\%$ conversion with $>80\%$ selectivity for 1,2-epoxyoctane at 1 mol % (Table 1).[17] If catalyst loading is reduced to 0.1 mol %, significant differentiation among these complexes is observed. Only four complexes provide $>75\%$ yield of 1,2-epoxyoctane within 5 min using 2 equiv of oxidant at 25 °C: $[Mn^{II}($**Me_3tacn**$)]^{2+}$, $[Mn^{II}($***R,R*-mcp**$)]^{2+}$, $[Mn^{II}($**bpma**$)]^{2+}$, and $[Mn^{II}($**bipy**$)_2]^{2+}$. Of all complexes tested, $[Mn^{II}($**bipy**$)_2]^{2+}$ shows the highest turnover frequencies (>1000 turnovers/min) (Table 1).

The **bipy** ligand has an optimal combination of oxidative stability and binding proclivity. The X-ray structure of $[Mn^{II}($**bipy**$)_2(CF_3SO_3)_2]$ shows both triflates bound in a cis fashion, similar to the coordination geometry of $[Mn^{II}($***R,R*-mcp**$)(CF_3SO_3)_2]$.[2,18] Mn^{II} complexes with a similar arrangement of labile ligands generally provide potent catalysts for terminal olefin oxidation, but this coordination geometry does not ensure efficient reactivity under all conditions. Relative to the octahedral complexes with cis labile sites, manganese complexes with tetradentate ligands that bind within the equatorial plane, creating two trans labile sites, show limited reactivity toward terminal olefins (**Me_4-cyclam** and **H_2-cdb**, Table 1, entries 11 and 13). The reactivity differences are highlighted when the conversion of 1-octene at 15 s is compared among the catalysts (Table 1). Complexes with cis labile sites generally catalyze the reaction faster than complexes with only trans labile sites. Anionic ligation also seems to attenuate the epoxidation rate (Table 1, entries 12 and 13). The limited reactivity of Mn–salen and Mn–porphyrin complexes toward terminal olefins is well documented.[19,20]

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[13] Complexes with acetate anions have been found to have reactivity identical to that of the triflate complexes.

[14] Catalysis stops within 15 min for most catalysts.

[15] Lane, B. S.; Burgess, K. *J. Am. Chem. Soc.* **2001**, *123*, 2933.

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[17] Highest induction observed with ligands **1**–**5**, **12**, **13**, and **17** under these conditions is $\leq 15\%$.

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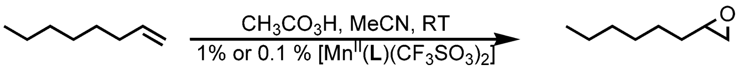
Table 1. Epoxidation Reactivity of $[Mn^{II}L(CF_3SO_3)_2]$ Complexes[a]



time		5 min		5 min				15 s[d]	
catalyst loading		PAA_C[b]		PAA_R[c]				PAA_R[c]	
oxidant		1%		1%		0.1%		1%	0.1%
	ligand	conversion	epoxide	conversion	epoxide	conversion	epoxide	epoxide	epoxide
1	*R*,*R*-mcp	98	94	96	92	96	92	75	27
2	*R*,*R*-pcp	0	0	28	22	2	2	8	
3	*R*,*R*-6-Me-6′-H-mcp	18	15	91	88	36	31	19	
4	*R*,*R*-6-Me-mcp	6	2	60	55	6	4	10	
5	*R*,*R*-hcp	18	11	98	96	33	28	88	
6	*meso*-hcp	4	2	95	92	15	12	61	
7	mep	25	24	87	87	53	49	83	2
8	*uns*-mep	5	3	94	94	49	43	89	
9	bisp	97	91	92	84	23	18	19	
10	tmpa	3	2	96	92	6	4	23	
11	Me_4cyclam	5	2	11	11	1	1	1	
12	*R*,*R*-H_1pcdb[e]	6	6	51	49	6	5	50	
13	*R*,*R*-H_2cdb[e]	4	2	20	15	1	1	3	
14	Me_3tacn	80	71	95	91	85	82	44	8
15	terpy	2	1	94	91	50	46	84	43
16	bpma	0	0	88	83	82	77	83	2
17	*R*,*R*-tmcp	12	9	95	92	15	11	74	
18	tmep	1	1	88	86	10	9	57	
19	bipy[f,g]	2	2	99	95	99	94	94	93
20	none	0	0	4	2	4	2	0	0

[a] Performed with 1-octene (0.5 M), $[Mn^{II}\mathbf{L}(CF_3SO_3)_2]$ (5 mM), *n*-nonane (50 mM), 2 equiv of CH_3CO_3H, 25 °C, 5 min. Conversion and epoxide yields determined relative to an internal standard. Results are average of at least three runs. [b] 32% CH_3CO_3H, 1% H_2SO_4 in CH_3CO_2H/H_2O (**PAA_C**). [c] 9−10% CH_3CO_3H in CH_3CO_2H (**PAA_R**). [d] 1-Octene (0.5 M), $[Mn^{II}\mathbf{L}(CF_3SO_3)_2]$ (5 mM), *n*-nonane (50 mM), 2 equiv of CH_3CO_3H (**PAA_R**), 25 °C. Reactions were quenched with Et_3N after 15 s. [e] $[Mn^{III}\mathbf{L}OAc]$ complexes, generated from $Mn^{II}OAc_2{\cdot}4H_2O$ and O_2. [f] Performed with 2 equiv of **bipy**/Mn^{II} [g] Phenanthroline shows reactivity nearly identical to that of bipy under these conditions.

Ostensibly small perturbations of the ***R*,*R*-mcp** framework impact dramatically the efficiency of the manganese catalysts. While most complexes examined are capable of complete conversion of 1-octene at 1% loading using **PAA_R**, substitutions that reduce the oxidative or kinetic stability of the complexes limit the overall turnover numbers of the catalyst. The introduction of additional benzylic hydrogens via 6-methyl substituents on the pyridyl rings provides not only a potential point of ligand oxidation but also reduces the thermodynamic stability of the formed metal complex.[21] A stepwise reduction in activity is seen with $[Mn^{II}($***R*,*R*-mcp**$)]^{2+}$, $[Mn^{II}($***R*,*R*-6-Me-6′-H-mcp**$)]^{2+}$, and $[Mn^{II}($***R*,*R*-6-Me-mcp**$)]^{2+}$ (Table 1, entries 1, 3, and 4). A similar reduction in epoxidation efficiency at 0.1% loading is observed when the backbone methyl groups are replaced with hydrogen atoms (i.e., $[Mn^{II}($***R*,*R*-hcp**$)]^{2+}$, Table 1, entry 5). Less thermodynamically stable complexes formed from diamines other than *trans*-1,2-cyclohexyl-diamine are also not as effective at 0.1 mol % catalyst (i.e., $[Mn^{II}($***meso*-hcp**$)]^{2+}$ and $[Mn^{II}($**mep**$)]^{2+}$, Table 1, entries 6 and 7). Although a wide variety of bispyridyl-diamine ligands are easily synthesized, $[Mn^{II}($***R*,*R*-mcp**$)]^{2+}$ is by far the most efficient catalyst within this family of complexes found to date.

The ligand structure also influences the relative rates of reactivity of the various manganese catalysts toward electronically and sterically distinct olefins. A characteristic epoxidation reactivity profile can be measured for each manganese complex using an intermolecular competition reaction in which a mixture of four distinct olefin substrates are oxidized under limiting oxidant conditions (Table 2). The relative ratio of the epoxides formed probes indirectly the nature of the metal-based oxidant and allows each catalyst's electronic and steric preferences for substrate to be compared. The starting concentrations of the four substrates were biased to ensure that a measurable conversion of each substrate occurs under these conditions; the relative starting concentrations of cyclooctene/dihydrocarvone/1-octene/*trans*-methylcinnamate were 1:10:10:20. The ratio of epoxides of these substrates reflect neither the absolute rate of epoxidation for each catalyst nor their catalytic efficiencies.

The discrimination between *cis*-cyclooctene and *trans*-methylcinnamate is a combination of electronic and steric

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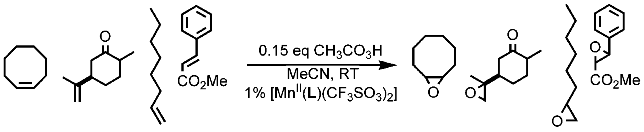
Table 2. Intermolecular Competition Studies of Catalysts



(1:10:10:20)

ligand	corrected relative ratio of epoxides formed CO:DH:O:MC[a]
Me_3tacn (**14**)	1500:20:10:1
bisp (**9**)	1400:20:10:1
bpma (**16**)	1100:30:20:1
Me_4cyclam (**11**)	1100:20:5:1
R,*R*-H_2cdb[b] (**13**)	1000:20:5:1
R,*R*-H_1pcdb[b] (**12**)	900:20:10:1
R,*R*-tmcp (**17**)	900:20:10:1
R,*R*-6-Me-mcp (**4**)	900:15:10:1
meso-hcp (**6**)	700:20:10:1
terpy (**15**)	700:10:5:1
tmep (**18**)	700:15:10:1
R,*R*-6-Me-6′-H-mcp (**3**)	700:15:10:1
uns-mep (**8**)	650:15:10:1
bipy (**19**)	600:20:10:1
R,*R*-pcp (**2**)	550:15:5:1
tmpa (**10**)	500:10:5:1
R,*R*-mcp (**1**)	300:10:5:1
mep (**7**)	200:10:5:1

[a] Cyclooctene (CO, 0.025 M), (+)-dihydrocarvone (DH, 0.25 M), 1-octene (O, 0.25 M), *trans*-methylcinnamate (MC, 0.5 M), nitrobenzene (0.0125 M), $[Mn^{II}(\mathbf{L})(CF_3SO_3)_2]$ (2.5 mM), and 9% CH_3CO_3H (0.15 M) in CH_3CN, 25 °C. The epoxide yields are determined relative to the internal standard. The values are the average of at least three runs. The relative ratios of epoxide are corrected for different initial concentrations. [b]$[Mn^{III}\mathbf{L}OAc]$ complexes, generated from $Mn^{II}OAc_2{\cdot}4H_2O$ and O_2.

effects. Some catalysts, such as $[Mn^{III}($***R,R*-cdb**$)]^+$ and $[Mn^{II}($**Me_3tacn**$)]^{2+}$, are cis selective because of the steric constraints of the approach of *trans*-olefins toward the activated metal species. The relative ratios of epoxide products observed here correlate well with the previously observed *cis*-olefin preference under different oxidation conditions.[16,22] While $[Mn^{II}($***R,R*-mcp**$)]^{2+}$ shows very little preference for *cis*-olefins over *trans*-olefins,[2] there remains a significant preference for *cis*-cyclooctene over *trans*-methylcinnamate due to the different electronic properties of the two substrates, the former being more electron rich than the latter. Synthetically, $[Mn^{II}($***R,R*-mcp**$)]^{2+}$ is a relatively indiscriminate oxidant, which shows good regioselectivity with a diolefin only when large electronic differences exist between the two double bonds.[2]

Screening a series of Mn^{II} complexes for terminal olefin epoxidation allows the identification of several Mn^{II} catalyst that are capable of high activity using **PAA_R** as the oxidant. The most active catalyst, $[Mn^{II}($**bipy**$)_2]^{2+}$, combines high activity with a simple, oxidatively robust ligand. This simple complex shows that high activity and stability can be achieved without resorting to more extreme strategies such as very electron-deficient[23] or complicated ligands.[24] Further optimization and exploration of substrate scope and mechanism is in progress.

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Supporting Information Available: Experimental procedures for the synthesis of novel ligands, catalysts, and peracetic acid solutions and reaction conditions and procedures for isolated yields using $[Mn^{II}($**bipy**$)_2(CF_3SO_3)_2]$. This material is available free of charge via the Internet at http://pubs.acs.org.

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