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Efficient and Selective Peracetic Acid Epoxidation Catalyzed by a Robust Manganese Catalyst

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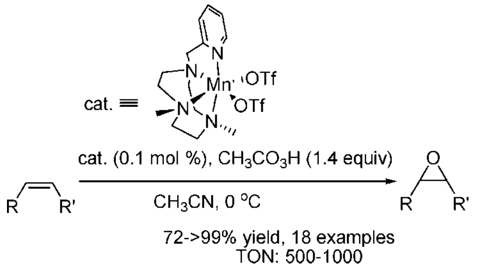
ABSTRACT



A manganese catalyst containing a tetradentate ligand derived from triazacyclononane exhibits high catalytic activity in epoxidation reactions using peracetic acid as oxidant. The system exhibits broad substrate scope and requires small (0.1−0.15 mol %) catalyst loading. The catalyst is remarkably selective toward aliphatic *cis*-olefins. Mechanistic studies point toward an electrophilic oxidant delivering the oxygen atom in a concerted step.

Development of environmentally benign and selective epoxidation methods with broad substrate scope under mild conditions is an important research topic because epoxy compounds are widely used as intermediates to obtain value-added chemical products. This has fueled the development of oxidation technologies based on the activation of peroxides by transition-metal catalysts.[1] Very recently, Stack and co-workers described [$Mn^{II}(CF_3SO_3)_2$(MCP)] (MCP = *N*,*N*′-dimethyl-*N*,*N*′-bis(2-pyridylmethyl)cyclohexane-*trans*-1,2-diamine) and $[Mn(bpy)_2]^{2+}$ (bpy = 4,4′-bipyridine) as very active epoxidation catalysts in combination with peracetic acid.[2] Peracetic acid is an environmentally friendly oxidant that only generates acetic acid as byproduct. Although this represents smaller atom efficiency compared to O_2 and H_2O_2, and it is comparatively more expensive than H_2O_2, most interestingly, it bypasses the common peroxide disproportionation reactions associated with the latter. Via wide screening of a number of catalysts, Stack and co-workers also demonstrated that the efficiency and selectivity of the reactions, as well as the catalyst stability, are dramatically modulated by their structure,[2] thus opening the door for the development of selective catalysts via careful ligand design.[3] Inspired by this idea, in this work we describe a novel Mn complex as a very efficient epoxidation catalyst capable of selectively epoxidizing a wide range of olefins reaching turnover numbers of 1000 at >98% conversion and >99%

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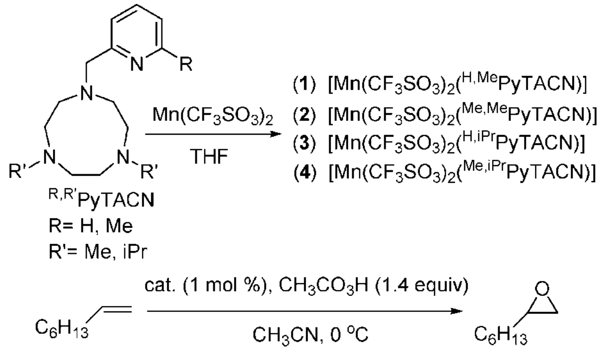
selectivity. The system also exhibits a remarkable selectivity for *cis*-aliphatic olefins.

We targeted the preparation and study of a novel family of Mn catalysts based on a triazacyclononane macrocyle, derivatized with a pyridylmethyl group because we envisioned that this structure would form highly stable and robust complexes under oxidative and/or acidic conditions. Indeed, Me_3TACN-based Mn complexes are well-known as quite robust epoxidation catalysts.[4] To this end, tetradentate ligands $^{R,R'}$PyTACN were prepared following standard procedures for the alkylation of dialkyl-substituted triazacyclononane backbones.[5] The corresponding complexes of general formula $[Mn(CF_3SO_3)_2(^{R,R'}PyTACN)]$ **1**−**4** were subsequently obtained by straightforward reaction of each ligand with $Mn(CF_3SO_3)_2$ in THF (Scheme 1, top). The complexes were isolated as colorless crystalline compounds in 57−85% yields. We initially tested their ability to epoxidize 1-octene in a 1 mol % catalyst scale and delivering commercially available peracetic acid via syringe pump over 3 min (Scheme 1, bottom). A remarkable dependence of the catalytic activity on the catalyst structure was observed. Both **3** and **4** are virtually inactive (1% epoxide yield), **2** is moderately active (27%), but most remarkably, the activity of **1** exhibits a rewarding 97% epoxide yield. On the basis of these preliminary experiments, further studies were restricted to **1**. An elliposoid diagram of the crystal structure of **1** is showed in Figure 1, which consists in a mononuclear Mn^{II} complex with a distorted octahedral geometry. Four coordination sites are occupied by the N atoms of the tetradentate ^{H,Me}PyTACN ligand, and the two remaining positions are occupied by the two oxygen atoms of triflate groups. The structure also shows that this type of ligand enforces the *cis* coordination of the CF_3SO_3 ligands, where the peracid molecule will most likely interact with the Mn ion.

Scheme 1



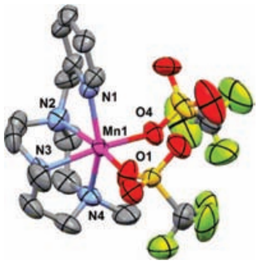


Figure 1. Ellipsoid diagram (50% probability) of **1**.

We developed reaction procedures to optimize the activity of **1** under lower catalyst loading conditions (cat. 0.1−0.15 mol %) using peracetic acid diluted in CH_3CN (1:1 v/v) and added at 0 °C over 30 min. Under these conditions (Table 1), catalyst **1** exhibits an excellent performance in the epoxidation of a wide range of olefins. Oxidations proceed smoothly between 1 and 6 h to reach completion revealing a remarkable stability of the catalyst. Thus, styrene and its derivatives (Table 1, entries 1−5) were epoxidized with excellent yields (91 to >99%). More challenging targets such as terminal aliphatic olefins were also efficiently and selectively oxidized to the corresponding epoxides (96 and 91% epoxide yields, 100% conversion, entries 13,14). Aliphatic *cis*-olefins proved particularly reactive substrates and they were epoxidized in quantitative yields and selectivities (entries 8−10). Remarkably, the oxidation of cyclohexene was chemoselective toward the epoxide, and only trace amounts (<1%) of allylic oxidation products were obtained. On the other hand, trisubstituted and *trans*-olefins were efficiently oxidized, yet lower yields for the epoxide were obtained (72−86%, entries 11, 12, and 18). The system also epoxidizes electron-deficient olefins affording excellent yields (88−89%, entries 16 and 17). Finally, *cis*- and *trans*-stilbene (entries 6 and 7) proved difficult substrates for the system, and modest epoxide yields (24 and 58% respectively) were obtained at 0.1 mol % catalyst loading. Increase of the catalyst loading led to full substrate conversion but epoxide yields decreased substantially.

Besides being a very active catalyst, **1** also allows selective monoepoxidation of substrates containing two olefinic sites. (*R*)-(−)-carvone and 4-vinylcyclohexene (entries 15 and 19) were selectively epoxidized to 5,6-monoepoxide carvone (89% yield) and 4-vinylcyclohexane-1-epoxide (78% yield), respectively. Furthermore, the *cis*-olefin site in *trans*-2-*cis*-

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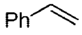
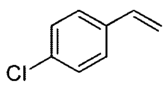
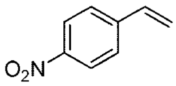
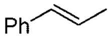
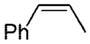
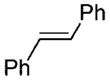
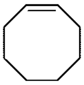
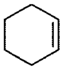
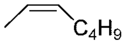
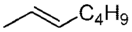
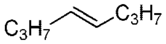
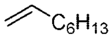
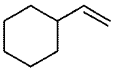
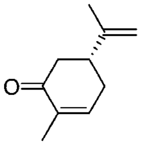
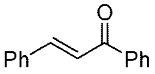
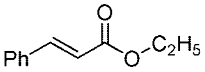
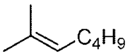
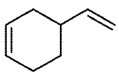
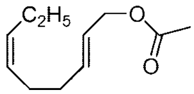
Table 1. Epoxidation of Different Olefins Using Catalyst[a]

entry	Substrate	cat.(%) / t (h)	convn %[b] (yield %)[c]	TON
1		0.1/1	100(91)	910
2		0.1/1	100(>99)	1000
3		0.1/6	100(>99)	1000
4		0.15/6	96(92)	615
5		0.1/2	98(93^{d})	970
6		0.1/1	86(58)	580
7		0.1/1	26(24^{e})	240
8		0.1/1	100(>99)	1000
9		0.1/1	100(>99)	1000
10		0.1/2	100(>99^{f})	1000
11		0.1/6	98(72)	720
12		0.15/6	89(72)	480
13		0.15/6	100(96)	640
14		0.15/6	100(91)	610
15		0.1/1	100(89^{g,h})	890
16		0.1/1	99(88^{h})	880
17		0.1/1	90(89^{h})	890
18		0.1/3	100(86)	860
19		0.1/1	99(78^{g,i})	780
20		0.1/1	100(96^{g})	960

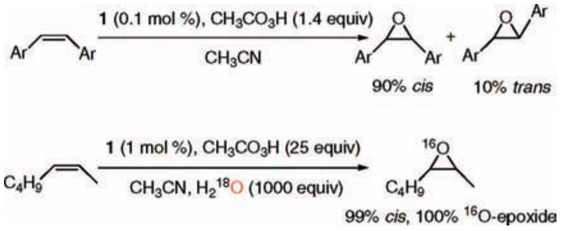
[a] Reaction conditions: olefin 0.12 M, catalyst **1** (0.1−0.15 mol %) 0.12/0.17 mM and 1.4 equiv of CH_3CO_3H 32% dissolved in CH_3CN (1:1) added over 30 min at 0 °C. **1**/CH_3CO_3H/olefin 1−1.5:1400:1000. See the Supporting Information for blank experiments. [b] Substrate conversion into products. [c] Unless stated, epoxide yield determined by GC. [d] 97% *cis*. [e] 90% *cis*. [f] 99% *cis*. [g] 1 equiv of CH_3CO_3H; yield refers to monoepoxide. [h] Yield determined by ^{1}H NMR. [i] 8% diepoxide.

6-nonadienyl acetate was selectively epoxidized to furnish the 6-monoepoxide 2-*trans*-olefin product in 96% yield (entry 20).

The chemoselectivity of **1** was further explored by performing competition experiments between pairs of olefins ([cat.]/[CH_3CO_3H]/[olefin A]/[olefin B] = 1:100:1000:1000). These experiments indicate that styrene is 14 times more reactive than *cis*-2-heptene and that the latter is 9 times more reactive than *trans*-2-heptene. This selectivity toward aliphatic *cis*-olefins is more pronounced than in stoichiometric oxidations using *m*-CPBA (1.2),[6] dimethyldioxirane (8.3),[7] catalytic systems such as Venturello's tungstate−H_2O_2 catalyst (3.7−7.3),[6] Mn−Me_3TACN−H_2O_2 and related catalysts (2.0−4.7),[4e] [$Mn^{II}(CF_3SO_3)_2$(MCP)]−CH_3CO_3H catalysts (3),[2a] iron−PhIO[8] (5.8 for *cis*/*trans*-2-butene), and manganese−NaOCl porphyrin catalysts (5.0 for *cis*/*trans*-2-hexene)[9] and approaches the high selectivity observed for Mizuno's silicotungstate−H_2O_2 system (11.5).[10] On the other hand, *cis/trans* selectivity is dramatically altered upon inclusion of aromatic rings in the olefin. Thus epoxidation of *cis*- and *trans*-β-methylstyrene occurs at identical rates, and *trans*-stilbene is two times more reactive than *cis*-stilbene. The inversion in the *cis/trans* selectivity upon changing from aliphatic to aromatic olefins suggests that its origin is not a pure topological discrimination.

First insight into the active species responsible for this chemistry was obtained by competitive oxidation of styrene versus *p*-substituted styrenes. A Hammett plot analysis of the data provides a $\rho = -0.67$ ($R^2 = 0.98$) indicating that an electrophilic type of active oxidant is active in these reactions. This value is in agreement with that determined for Mn−Me_3TACN−H_2O_2 catalyzed epoxidation of cinnamic acids ($\rho = -0.63$).[11] On the other hand, epoxidation of *cis*- and *trans*-olefins exhibit a large degree of stereospecificity. Only trace amounts of epimerized products were detected in the epoxidation of aliphatic olefins and β-methylstyrenes, and only 10% of epimerized epoxide was obtained in the epoxidation of the very sensitive *cis*-stilbene (Scheme 2, top). These observations rule out the implication of long-lived carbocationic and/or radical type of intermediates, which are commonly involved in epoxidations by Mn−salen,[12] Mn−Me_3TACN,[4d] and Mn salts in bicarbonate

Scheme 2



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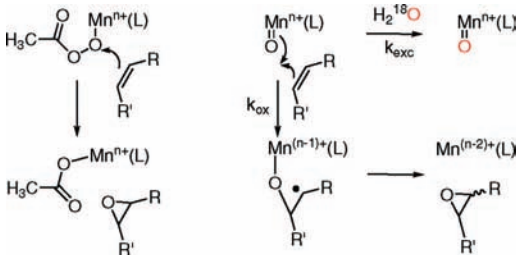
buffer.[13] Finally, an epoxidation reaction of *cis*-2-heptene (100 equiv substrate/25 equiv CH_3CO_3H) in the presence of large excess of $H_2{}^{18}O$ (1000 equiv) showed no incorporation of ^{18}O into the epoxide (Scheme 2, bottom) indicating that the oxidant does not exchange with water. Although high-valent manganese-oxo species usually undergo exchange of the oxo oxygen atom with water,[14] the present observation should be taken with caution, as failure to see ^{18}O-exchange is not a definitive proof to rule out the implication of manganese oxo species. It is possible that water exchange may be simply slower than attack on the substrate (Scheme 3, $k_{exc} \ll k_{ox}$), precluding tautomerization.

Scheme 3



At present, the absence of both intermediate accumulation and observation of water incorporation into products preclude the identification of the active species responsible for this chemistry. Indeed, the exact nature of the epoxidation species in other manganese systems such as porphyrins,[15] salen,[12] Me_3TACN,[4d,16] and also in recently described nonporphyrin type of complexes[2,3,17] remains a matter of debate. This chemistry is found to be highly sensitive to the catalyst nature, oxidant and reaction conditions, which suggests the presence of a diverse mechanistic landscape. In general, two basic mechanistic scenarios are proposed. The first one implicates high-valent (usually Mn^V) Mn−oxo species (Scheme 3, right) as responsible for the oxygen atom transfer event.[12] More recently, it has also been proposed that the oxidant may be Lewis acid activated by a high valent (Mn^{IV} or Mn^V) species (Scheme 3, left).[17] We favor the latter explanation because oxygen atom transfer from peracid type of species is a concerted reaction,[18] while significant loss of stereochemistry in *cis*-stilbene epoxidation is commonly observed in oxidations by high valent metal oxo species.[12,15] This mechanistic scenario would also account for the lack of water exchange in these reactions. However, none of the two arguments is indeed conclusive.

In conclusion, the present work describes a novel catalyst which epoxidizes a wide range of olefins with excellent efficiency and remarkable selectivity under mild experimental conditions. The method is environmentally non aggressive, and the reactions only require 1.0−1.4 oxidant/substrate molar ratio. Substrate conversions are quantitative (or nearly), and selectivities for the epoxide usually surpass 90%. Most remarkably, the catalyst is very robust and supports turnover numbers that range from 500 to 1000, which results in minimum catalyst loadings. The present system compares well with state of the art $Mn-Me_3TACN-oxalate-H_2O_2$,[4f] and $[Mn^{II}(CF_3SO_3)_2(MCP)]-CH_3CO_3H$-based systems[2] in terms of epoxide yields, stereochemical retention, catalyst activity and broad substrate scope. Despite the fact that the laborious preparation of the tetradentate ^{H,Me}PyTACN ligand still constitutes a drawback when compared with commercially available Me_3TACN and the relatively simple three-step synthesis of MCP,[2a] **1** exhibits a much more pronounced discrimination between structurally different aliphatic olefin sites, which allows the site selective epoxidation of polyolefins. Finally, preliminary mechanistic studies indicate the implication of an electrophilic oxidant capable of delivering the oxygen atom to the olefin in a concerted step.

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Supporting Information Available: Experimental procedures and a CIF file for **1**. This material is available free of charge via the Internet at http://pubs.acs.org.

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