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Mn–trimethyltriazacyclononane/ascorbic acid: a remarkably efficient catalyst for the epoxidation of olefins and the oxidation of alcohols with hydrogen peroxide

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Abstract

The system comprised of manganese(II) acetate or sulfate, 1,4,7-trimethyl-1,4,7-triazacyclononane (TMTACN) and ascorbic acid efficiently catalyzes the epoxidation of olefins and the oxidation of alcohols with hydrogen peroxide. For example, in the presence of as little as 0.03 mol% of Mn^{2+}, methyl acrylate is converted to its epoxide in 97% yield. Under the same conditions, 2-pentanol yielded 2-pentanone in almost quantitative yield. With *E*- and *Z*-1-deuterio-1-octene as substrates, the epoxidation was shown to proceed with almost exclusive (94±2%) retention of configuration. © 1999 Elsevier Science Ltd. All rights reserved.

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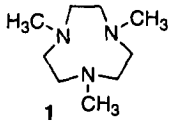
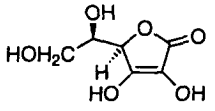
The catalytic oxidation of olefins to epoxides is an extremely important transformation, both from an academic and an industrial point of view. Many efforts in this field are directed towards the efficient use of hydrogen peroxide as the terminal oxidant: H_2O_2 is a cheap and mild reagent, with only water being formed as a side product.[1] As far as manganese catalysts are concerned, complexes of the ligand TMTACN (1,4,7-trimethyl-1,4,7-triazacyclononane, **1**) have recently attracted considerable attention.[2–6]



1



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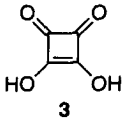

3

The activity of Mn–TMTACN as an epoxidation catalyst was described in 1994.[3] However, attempts to use Mn–TMTACN for preparative purposes were frustrated by the pronounced catalase activity of this material.[2–4] A significant improvement resulted from the discovery that the decomposition of hydrogen peroxide is suppressed at subambient temperatures and by using acetone as solvent.[5,6] Under these conditions, Mn–TMTACN was also found to catalyze the oxidation of benzylic alcohols with H_2O_2,

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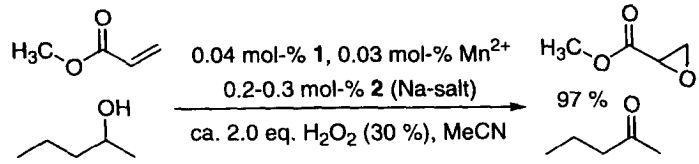
affording benzaldehydes.[7] Recently, De Vos et al. showed that the addition of oxalate buffer as co-ligand strongly enhances the epoxidizing activity of the Mn–TMTACN catalyst.[8] For example, in the presence of 0.15 mol% of Mn–TMTACN and 0.3 mol% of oxalate, allyl acetate or 1-hexene could be transformed to the corresponding epoxides in almost quantitative yields. With this in mind, we reasoned that co-ligands other than oxalate may have the same or even a stronger activating effect on the H_2O_2/Mn–TMTACN system, and that chiral, enantiomerically pure co-ligands might afford enantiomerically enriched epoxides. In fact, enantiomerically enriched epoxides have already been obtained by a related approach, using chiral derivatives of the TACN ligand, but without external co-ligands.[9] We herein report that the screening of a variety of potential co-ligands identified ascorbic acid (**2**) as a highly efficient and readily available activator. Our catalytic system oxygenates olefins to epoxides and oxidizes alcohols to carbonyl compounds with extreme efficiency (Eq. 1).[10] Using *E*- and *Z*-1-deuterio-1-octene as substrates, we could show that the epoxidation is stereospecific.[11]



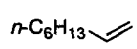
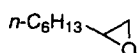
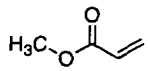
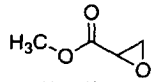
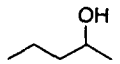
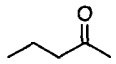
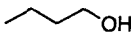
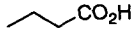
(1)

The idea to induce asymmetry by a chiral co-ligand first led us to screen amino acids, *N*-sulfonyl amino acids and *N,N'*-disulfonyl 1,2-diamines (e.g. derivatives of 1,2-diaminocyclohexane). 1-Octene was used as the test-substrate, and the reaction conditions were those described by De Vos.[8] Of course, the additives to be screened replaced the oxalate buffer. In this series, only aspartic acid and *N*-tosyl glycine proved useful as activators. Unfortunately, neither aspartic acid nor any other chiral co-ligand afforded enantiomerically enriched epoxides, i.e. 1,2-epoxyoctane. We then turned to dicarboxylic acids. From the large number of (chiral and achiral) diacids tested, squaric acid **3** proved particularly effective. The structural similarity between **3** and ascorbic acid **2** led us to the assumption that much more readily available **2** might have comparable activating properties. To our delight, this assumption turned out to be correct: As shown in Table 1, the efficiency of the Mn–TMTACN/ascorbic acid catalyst even surpasses that of the Mn–TMTACN/oxalate system.[8] As typical examples for terminal or electron deficient olefins, 1-octene (Table 1, entry 1) and methyl acrylate (Table 1, entry 2) were chosen. For 1-octene, the olefin:Mn ratio achieved (1333:1) is already twice as high as that of the oxalate system (typically 666:1).[8,12] The most remarkable result was obtained in the epoxidation of methyl acrylate (Table 1, entry 2): in this case, as little as 0.03 mol% of the catalyst were sufficient for full conversion of the substrate.[12,13,15] This value corresponds to more than 3000 catalyst turnovers, and the epoxidation is usually complete after ca. 2 h. The same efficiency was observed for the oxidation of secondary alcohols. As shown in Table 1 (entry 3), 2-pentanol was converted to 2-pentanone under virtually identical conditions.[12,14,15] The oxidation of primary alcohols such as 1-butanol (Table 1, entry 4) requires larger amounts of catalyst. Nevertheless, the almost quantitative conversion of 1-butanol to butyric acid (Table 1, entry 4) can still be achieved with less than 0.5 mol% of Mn. In all oxidations investigated, the exclusion of air was not necessary.

For potential applications in catalytic organic synthesis, the oxygen transfer to the substrate olefins should occur stereospecifically, preferentially with retention of configuration. We chose *E*- and *Z*-1-deuterio-1-octene as test substrates.[11] ^{1}H NMR analysis of the resulting epoxides revealed that indeed the configuration of the starting olefin was retained to 94±2% in both cases.[16]

In summary, we have discovered a novel, cheap and readily available co-ligand for the Mn–TMTACN-catalyzed epoxidation of terminal olefins with hydrogen peroxide. At present, we have no clearcut information on the structure of the Mn–TMTACN species that is active in the catalytic cycle. Nevertheless,

Table 1
Epoxidation of olefins and oxidation of alcohols with hydrogen peroxide

Entry	Substrate	Stoichiometry substrate:H_2O_2: Mn:TMTACN	Stoichiometry Mn:ascorbic acid: sodium ascorbate	Product[a] (yield)[b]
1		1333:3500: 1:1.3	1:0.5:2.1	 (83 %)
2		3333:6666: 1:1.3	1:0:8	 (97 %)
3		3333:8000: 1:1.3	1:0:6.7	 (97 %)
4		267:667: 1:1.3	1:0.5:2	 (90 %)

[a]In all cases, the products were isolated and identified by comparison of their spectroscopical data with those of authentic samples.
[b]Determined by capillary GC.

to the best of our knowledge, the efficiency of our Mn–TMTACN/ascorbate system is the highest one reported so far: Full conversion of the substrate olefins was achieved at catalyst loadings of less than 0.1%. Furthermore, the oxygen transfer catalyzed by Mn–TMTACN/ascorbate occurs with retention of configuration, i.e. in a stereospecific manner. The same outstanding efficiency was observed for the Mn–TMTACN/ascorbate-catalyzed oxidation of secondary alcohols with hydrogen peroxide.

Acknowledgements

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J.; Aoki, M.; Noyori, R. *Tetrahedron Lett.* **1998**, *39*, 7549–7552; Sato, K.; Aoki, M.; Takagi, J.; Noyori R. *J. Am. Chem. Soc.* **1997**, *119*, 12386–12387. For recent developments in rhenium-catalyzed oxidation of alcohols and epoxidation of olefins, see: Zauche, T. H.; Espenson, J. H. *Inorg. Chem.* **1998**, *37*, 6824–6831; Adolfsson, H.; Converso, A.; Sharpless, K. B. *Tetrahedron Lett.* **1999**, *40*, 3991–3994.

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12. As in the case of the Mn/oxalate system, control experiments showed that all three components, i.e. Mn^{2+}, TMTACN and co-ligand, are required for catalytic activity.
13. Procedure for the epoxidation of methyl acrylate: In a 10 mL round-bottomed flask, eqipped with a stir bar, the following components were added to 861 mg (10.0 mmol) of methyl acrylate: 0.5 mL of acetonitrile, 100 µL of a 40 mM stock solution of TMTACN in acetonitrile, 20 µL of a 150 mM stock solution of manganese(II) acetate tetrahydrate in water, 300 µL of a 80 mM stock solution of sodium ascorbate in water and 100 µL of water. The mixture was cooled to 0°C, and 2.0 mL (ca. 20 mmol, 2 equiv.) of non-stabilized 30% aqueous hydrogen peroxide were added in portions of ca. 0.2 mL. For GC-analysis, 100 µL samples were withdrawn, diluted with 1 ml of dichloromethane, and MnO_2 was added to destroy excess H_2O_2. When the evolution of gas had ceased, the solutions were analyzed after filtration through a cotton plug. In a preparative run, 2.58 g (30.0 mmol) of methyl acrylate afforded 2.41 g (23.6 mmol, 79%) of the analytically pure epoxide after extraction and fractional vacuum distillation.
14. Procedure for the conversion of 2-pentanol to 2-pentanone: In an analogous manner, 1.0 mL of acetonitrile, 100 µL of the TMTACN stock solution, 20 µL of the manganese(II) acetate solution, 250 µL of the sodium ascorbate solution and 0.8 mL of water were added to 900 mg (10.0 mmol) of 2-pentanol. The oxidation was performed as described above at 0°C, using a total of 2.5 mL (ca. 25 mmol, 2.5 equiv.) of non-stabilized 30% hydrogen peroxide.
15. The efficiency of the reaction was found to be dependent on the amount of water present *prior* to the addition of hydrogen peroxide: Less polar substrates like, e.g. 1-octene gave better yields at lower water contents and under more dilute conditions (see experimental procedures in Refs. 13 and 14). When the initial water addition was completely omitted, a substantial decrease in turnover resulted, along with an increase in hydrogen peroxide decomposition. On the other hand, the water content of the oxidant itself did not seem to be of major importance.
16. Retention of configuration was also observed in the Mn–TMTACN/oxalate-catalyzed epoxidation of *E*- and *Z*-2-hexene with hydrogen peroxide: see Ref. 8. In the absence of co-ligands, the Mn–TMTACN-catalyzed epoxidation proceeds with much lower stereospecificity: see Refs. 5, 6 and 9.