Polymer-Supported Ruthenium Porphyrins: Versatile and Robust Epoxidation Catalysts with Unusual Selectivity

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Received February 7, 2000

Abstract: Carbonyl ruthenium(II) 5,10,15-tris(4-R-phenyl)-20-(4-hydroxyphenyl)porphyrins (R = Cl, Me) covalently attached to Merrifield's peptide resin were prepared. The catalyst with R = Cl was found to efficiently catalyze Cl_2pyNO epoxidation of a wide variety of alkenes, including aromatic and aliphatic terminal alkenes, *cis*- and *trans*-stilbene, cyclohexene and cyclooctene, α,*β*-unsaturated ketones, conjugated enyne, glycal, and protected α-amino alkene. Unusual selectivities were observed for the epoxidations of 1,5-cyclooctadiene, *cis*-1-phenyl-3-penten-1-yne (**9**), 3,4,6-tri-*O*-acetyl-D-glucal (**11**), and 2-(Boc-amino)-1-phenylbut-3-ene (**13**), which feature a complete bisepoxide selectivity (1,5-cyclooctadiene), unprecedentedly high cis:trans ratio (**9**), and complete diastereoselectivity (**11** and **13**). The new heterogenized metalloporphyrin epoxidation catalysts are of high stability and reusability.

Introduction

Epoxidation of unfunctionalized alkenes catalyzed by metalloporphyrins is a subject of tremendous investigations.[1] By tailoring the porphyrin macrocycles with steric hindrance, sophisticated chiral auxiliaries, or strongly electron-withdrawing groups, the homogeneous systems involving these catalysts can exhibit high regio-,[2a−d] shape-,[2c,e] and enantioselectivity[1b] and extremely high catalyst turnovers.[2f,g] However, these appealing features are usually outweighed by the relatively high costs of the catalysts and their applicability for rather limited types of alkenes, rendering their application to synthesis so far impractical. In fact, the majority of the studies are directed to understanding the mechanism of the catalytic activity of heme-containing enzymes such as cytochrome P-450.[1] Perhaps a potential approach to commercial metalloporphyrin catalysts is to immobilize them onto solid supports. Such immobilization can (i) make the catalysts readily separable from the products and reusable, (ii) enhance the catalyst stability toward oxidative degradation through efficient site-isolation, and (iii) allow preparation of environmentally friendly catalysts. It would further be beneficial if the heterogenized catalysts with required selectivity bear *simple* porphyrinato ligands and are applicable for a *wide* variety of alkenes.

The first alkene epoxidation employing a heterogenized metalloporphyrin catalyst was reported in 1983 by Nolte, Drenth, and co-workers,[3] who grafted a manganese *meso*-tetraarylporphyrin onto polyisocyanide, mainly to study the effect of site-isolation. Since then, a number of investigations on heterogenized metalloporphyrins as catalysts for alkene epoxidation have appeared in the literature.[4,5] However, almost all these studies are confined to iron and manganese porphyrins, which are usually sterically encumbered and/or have strongly electron-withdrawing groups, and involve only one or a few common alkenes such as cyclooctene, stilbene, and styrenes.[3,4] In no case have the heterogenized catalysts been reported to be as efficient as the corresponding homogeneous ones for a wide variety of alkenes. The partial loss of chemo- or stereoselectivity,[4c,l,5b] catalyst leaching,[4k,5b] and the significant or complete loss of catalytic activity toward some substrates[4e,5b] are among the problems encountered.

Herein we report on the first alkene epoxidation catalyzed by *polymer*-supported ruthenium porphyrins, which employ *simple* porphyrinato ligands and can readily be prepared yet exhibit a high versatility and stability, with complete diastereoselectivity in epoxidation of glycal and α-aminoalkyl alkene. The formation of aminoalkyl epoxides via catalytic oxidation of their alkene precursors has never been realized before.

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10.1021/ja000461k CCC: $19.00
Published on Web 05/20/2000

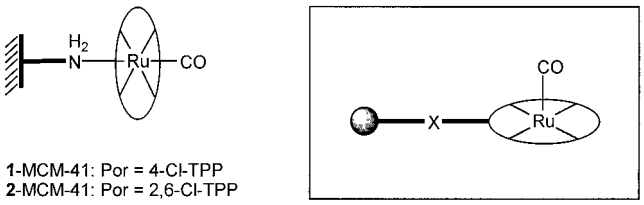

Figure 1. Schematic structures of ruthenium porphyrins (a) coordinatively grafted onto surface modified MCM-41 and (b) covalently attached to a solid support. 4-Cl-TPP = *meso*-tetrakis(4-chlorophenyl)-porphyrinato dianion; 2,6-Cl-TPP = *meso*-tetrakis(2,6-dichlorophenyl)-porphyrinato dianion.

Results and Discussion

The pioneering work by Groves and co-worker[6a] on ruthenium porphyrin-catalyzed alkene epoxidations, combined with the unique periodic relation of ruthenium to iron and the facile isolation of dioxoruthenium(VI) porphyrins, stimulated much recent interest in the utilization of ruthenium porphyrins as homogeneous catalysts in alkene epoxidation.[6b−r] However, heterogenized ruthenium porphyrin catalysts are rare, the first of which appeared in 1993 and were used to catalyze the decomposition of cyclohexyl hydroxide rather than alkene epoxidation.[7] We recently immobilized two ruthenium porphyrins, via *coordinative* bonding, onto a surface-modified mesoporous molecular sieve (MCM-41) to form the heterogenized catalysts **1**- and **2**-MCM-41 (Figure 1a), and examined their catalytic behavior toward alkene epoxidation.[5] While catalyst **2**-MCM-41, which contains a sterically encumbered porphyrinato ligand, has been found to effect highly selective alkene epoxidations by Cl_2pyNO,[5b] reuse experiments reveal significant catalyst leaching and/or deactivation. This stimulated our interest in attaching ruthenium porphyrins to a solid support through a *covalent* linkage, forming more stable catalysts as depicted in Figure 1b. On the other hand, the covalent attachment of porphyrin ligands to a solid support represents a unique type of porphyrin modification. By utilizing a simple porphyrin macrocycle and judiciously choosing the support, it is possible to obtain a heterogenized catalyst showing high selectivity as well as high stability.

Preparation of Polymer-Supported Ruthenium Porphyrins. The solid support used in the present work is the well-known Merrifield's peptide resin (abbreviated here as MPR), a chloromethylated styrene−divinylbenzene copolymer. This type of support can be considered as an "insoluble benzyl chloride",[8] and could readily react with compounds bearing appropriate functional groups such as hydroxyl. The excellent solvation and swelling of MPR in certain organic solvents such as dichloromethane and *N*,*N*-dimethylformamide (DMF)[9] may allow metalloporphyrins to be attached not only at the surface of the polymer bead but also within the interior of the cross-linked polymeric matrix. Consequently, there is a possibility of achieving a high selectivity by supporting sterically *unencumbered* ruthenium porphyrins onto MPR as a result of the unique microenvironment constituted by the porphyrin macrocycle and the polymer matrix. Moreover, owing to the solvation and swelling, the heterogeneous catalysis involving an MPR-supported catalyst would proceed rapidly (note that the previously reported hetereogenized metalloporphyrin catalysts often operate much more slowly than their homogeneous counterparts[4c,n]).

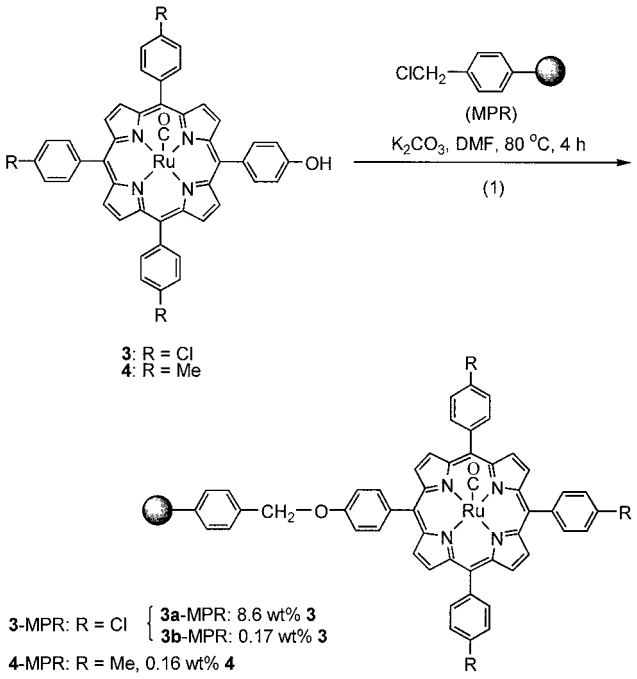

Figure 2. Synthesis of ruthenium porphyrins covalently immobilized onto Merrifield's peptide resin.

To obtain ruthenium porphyrins bearing a periphery hydroxyl group, we started from simple unsymmetrically substituted *meso*-tetraarylporphyrin free bases, 5,10,15-tris(4-R-phenyl)-20-(4-hydroxyphenyl)porphyrins (R = Cl, Me), which can be prepared readily via a "one-pot" reaction of the corresponding aldehydes and pyrrole.[10] Reaction of these porphyrins with $Ru_3(CO)_{12}$ in refluxing Decalin afforded ruthenium(II) porphyrins **3** and **4** depicted in Figure 2 in ca. 80% isolated yields. Complexes **3** and **4** exhibit intense IR bands at 1941 and 1942 cm^{-1}, respectively, characteristic of carbonylruthenium(II) *meso*-tetraarylporphyrins.[11] Subsequent ^1H NMR, UV/vis, and MS measurements, together with elemental analyses, further support their formulations (see Experimental Section).

The covalent attachment of **3** and **4** to MPR was realized by treating the complexes with MPR in DMF at 80 °C for 4 h in the presence of anhydrous potassium carbonate (reaction 1 in Figure 2). This is similar to the reaction between *meso*-tetrakis-(4-hydroxyphenyl)porphyrin and butyl bromide, which affords *meso*-tetrakis(4-butoxyphenyl)porphyrin in 95% yield.[10] The

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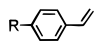
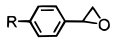
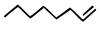
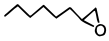
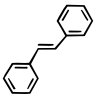
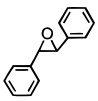
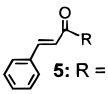
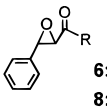
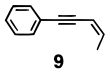
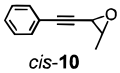
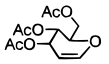
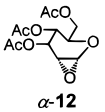
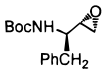
Table 1. Epoxidation of a Wide Variety of Alkenes with Cl_2pyNO Catalyzed by **3a**-MPR[a]

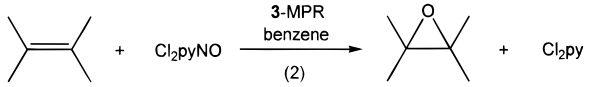
Entry	Substrate	Product		Yield (%)[b]	Entry	Substrate	Product	Yield (%)[b]
1			R=H	96[c]	12			76
2			F	89[c]				
3			Cl	94[c]				
4			Br	86[c]	13			91
5				97[c]				
6				90[c]	14	 **5:** R = Me	 **6:** R = Me	89
					15	**7**: R = OEt	**8:** R = OEt	87
7				86[c]	16	 **9**	 *cis*-**10**	91[e]
8				62	17	 **11**	 *α*-**12**	56[f,g]
9		 (*exo*-)		98				
10				66[d]	18	 (*R*)-**13**	 *threo*-**14**	88[f,h]
11				98				

[a] Unless otherwise specified, all reactions were carried out in benzene at room temperature for 24 h with a catalyst:oxidant:substrate molar ratio of 1:1400:1600. [b] Based on the amount of Cl_2py formed. [c] Trace amounts of the corresponding aldehyde were also detected. [d] Other products: cyclohex-2-en-1-one (25%) and cyclohex-2-en-1-ol (7.5%). [e] Yield of trans epoxide: 7%. [f] Reaction conditions: 40 °C, 48 h, catalyst:oxidant: substrate molar ratio of 1:610:600. [g] Overall isolated yield after epoxidation and methanolysis. [h] Isolated yield based on the amount of starting alkene.

resulting heterogenized catalysts are designated as **3**- and **4**-MPR, respectively. In the case of **3**-MPR, two catalysts with different **3** loadings (8.6 and 0.17 wt %) designated as **3a**- and **3b**-MPR, respectively, were prepared by changing the amount of **3** used for reaction 1. Evidence for the successful heterogenization includes the following: (i) The IR spectra of **3**- and **4**-MPR each show a ν(CO) band at ca. 1945 cm^{-1}, similar to the corresponding bands of **3** and **4**. (ii) The Raman spectrum of **3a**-MPR was examined, which is similar to that of **3** if the bands belonging to MPR are excluded. (iii) While the support MPR itself exhibits no activity toward alkene epoxidations, both **3**- and **4**-MPR are efficient catalysts for these kinds of reactions in a manner analogous to homogeneous ruthenium porphyrin catalysts (see below).

Alkene Epoxidation with 2,6-Dichloropyridine *N*-Oxide (Cl_2pyNO) Catalyzed by 3- and 4-MPR. It has been well established, first by Hirobe and co-workers,[6c] that substituted pyridine *N*-oxides, such as Cl_2pyNO, can efficiently epoxidize alkenes in the presence of homogeneous ruthenium porphyrin catalysts.[6c,d,f,p−r] Preliminary examinations of the catalytic behavior of **3b**-MPR and **4**-MPR toward epoxidation of styrene with Cl_2pyNO revealed that the catalyst **3**-MPR, which bears electron-withdrawing Cl groups, was superior to **4**-MPR, and higher yields of epoxides were obtained in benzene than in dichloromethane, toluene, or acetonitrile. Accordingly, unless otherwise indicated, all the results described below were obtained through reactions in benzene by employing the catalyst **3**-MPR (reaction 2, Scheme 1).

Scheme 1



(i) Versatility. To inspect the applicability of **3**-MPR for various types of alkenes, we first used the catalyst **3a**-MPR, which has a relatively high **3** loading. The results obtained for this catalyst at a catalyst:oxidant:substrate molar ratio of 1:1400:1600 are shown in Table 1. Evidently, **3a**-MPR is an efficient catalyst for epoxidation of a wide variety of alkenes. In the cases of styrene, *cis*-stilbene, norbornene, cyclohexene, cyclooctene, and 1-octene (entries 1, 5, 9, 10, 11, and 13, respectively), the epoxide yields and stereoselectivity for *cis*-stilbene and norbornene are comparable to those obtained by employing the catalyst **2**-MCM-41 with a sterically encumbered porphyrin. Surprisingly, **3a**-MPR is also efficient in catalyzing the epoxidation of *trans*-alkenes. For *trans*-stilbene and *trans*-*β*-methylstyrene, the yields of the corresponding trans epoxides were as high as 90 and 86% (entries 6 and 7), respectively, and no cis epoxides were detected. In contrast, **2**-MCM-41 was not found to be an effective catalyst for epoxidation of *trans*-alkenes. For example, **2**-MCM-41 is completely ineffective toward the epoxidation of *trans*-stilbene.[5b]

The epoxidation of the alkenes in entries 8, 12, 14−16, and 18 has not been catalyzed by any of the previously reported heterogenized metalloporphyrin catalysts.[3−5] The catalytic activity of **3a**-MPR toward epoxidation of electron-deficient alkenes, namely α,*β*-unsaturated ketones, is remarkable. For example, in the cases of alkenes **5** (entry 14) and **7** (entry 15), reaction

(11) Carbonyl ruthenium(II) *meso*-tetraarylporphyrins generally exhibit intense ν(CO) bands in the range of 1918−1965 cm^{-1}, see for examples: (a) Tsutsui, M.; Ostfeld, D.; Hoffman, L. M. *J. Am. Chem. Soc.* **1971**, *93*, 1820. (b) Bonnet, J. J.; Eaton, S. S.; Eaton, G. R.; Holm, R. H.; Ibers, J. A. *J. Am. Chem. Soc.* **1973**, *95*, 2141. (c) Brown, G. M.; Hopf, F. R.; Ferguson, J. A.; Meyer, T. J.; Whitten, D. G. *J. Am. Chem. Soc.* **1973**, *95*, 5939. (d) Eaton, S. S.; Eaton, G. R. *J. Am. Chem. Soc.* **1975**, *97*, 3660. (e) Rillema, D. P.; Nagle, J. K.; Barringer, L. F., Jr.; Meyer, T. J. *J. Am. Chem. Soc.* **1981**, *103*, 56. (f) Collman, J. P.; Barnes, C. E.; Swepston, P. N.; Ibers, J. A. *J. Am. Chem. Soc.* **1984**, *106*, 3500. (g) Collman, J. P.; Barnes, C. E.; Brothers, P. J.; Collins, T. J.; Ozawa, T.; Gallucci, J. C.; Ibers, J. A. *J. Am. Chem. Soc.* **1984**, *106*, 5151.

2 afforded the corresponding epoxides **6** and **8** in close to 90% yields. To our knowledge, even in the homogeneous systems, no metalloporphyrins are reported to be active catalysts for Cl_2-pyNO or PhIO epoxidation of these types of alkenes.[12]Although epoxidation of α,*β*-unsaturated ketones can be efficiently catalyzed by other metal complexes or polypeptides,[13] very few such reports deal with the epoxidation of alkenes **5** and **7**.[14]

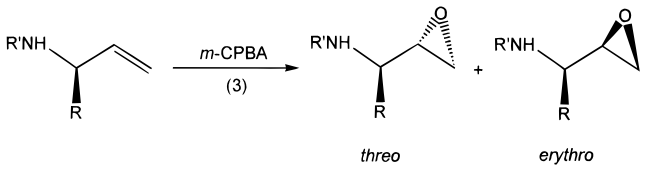
(ii) Unusual Selectivity. Besides the aforementioned versatility, another remarkable feature of **3a**-MPR lies in its unusual selectivity obtained for the following alkenes.

(a) 1,5-Cyclooctadiene. As shown in Table 1 (entry 12), reaction 2 (Scheme 1) for 1,5-cyclooctadiene afforded the corresponding *bisepoxide* in 76% yield. *No monoepoxide was detected*. This is contrary to the epoxidation of the same alkene with H_2O_2 catalyzed by molybdenum porphyrins[15a] and epoxidation of 1,3-cyclohexadiene in the NaClO−manganese porphyrin[15b] and PhIO−iron porphyrin systems,[2a] which all selectively produced the corresponding monoepoxide. Since excess 1,5-cyclooctadiene was used for reaction 2, and the monoepoxide of this alkene is a stable compound, the selective formation of its bisepoxide is very surprising.

(b) *cis*-1-Phenyl-3-penten-1-yne (9). The monoepoxides of conjugated enynes are valuable intermediates in organic synthesis[16] and, especially, are closely related to bioactive enediyne antitumor agents.[17] The applicability of reaction 2 for **9**, a simple enyne, was examined. Notably, this reaction afforded the corresponding epoxides *cis*- and *trans*-**10** in 91 and 7% yields, respectively (entry 16), with a cis:trans ratio of *13:1*, very different from the cis:trans ratio of *1:2* obtained for the epoxidation of the same alkene with NaClO catalyzed by a manganese−salen catalyst.[18]

(c) Glycal. Glycal epoxides are important intermediates for the synthesis of carbohydrates.[5b,19] We previously observed that, unlike the dioxirane oxidation of 3,4,6-tri-*O*-acetyl-D-glucal (**11**) which produced a mixture of epoxides α- and *β*-**12**,[19] a homogeneous ruthenium porphyrin catalyst, [Ru^{II}(2,6-Cl-TPP)(CO)(EtOH)], could catalyze the epoxidation of this substrate with Cl_2pyNO to form α-**12** only.[5b] However, immobilization of the ruthenium porphyrin onto MCM-41 to form **2**-MCM-41 resulted in a significant loss of the diastereoselectivity, producing a mixture of α- and *β*-**12** in a 3:1 ratio.[5b] Interestingly, by employing **3a**-MPR as catalyst with a catalyst:oxidant:substrate molar ratio of 1:610:600, the epoxidation of the glycal with Cl_2pyNO is completely diastereoselective—only α-**12** was obtained (entry 17).

Scheme 2



(d) Protected α-Amino Alkene. Protected aminoalkyl epoxides have attracted much attention in recent years owing to their utility in organic synthesis[20] and particularly in the preparation of several dipeptide isosteres for synthesizing the inhibitors of some key aspartic proteases such as renin[21] and HIV protease.[22] Such epoxides can be prepared from *stoichiometric* epoxidation of protected α-amino alkenes with *m*-chloroperoxybenzoic acid (*m*-CPBA), which exclusively affords *a mixture of threo and erythro diastereomers* (reaction 3, Scheme 2) with the threo diastereomer as the major products.[22b,e,23] To develop a catalytic epoxidation for these types of alkenes, we examined the applicability of reaction 2 to 2-(Boc-amino)-1-phenylbut-3-ene (**13**, Boc = *tert*-butoxycarbonyl), a typical protected α-amino alkene, whose *threo*-epoxide is a key intermediate for the synthesis of HIV-1 protease.[22b,d,23g] Remarkably, under the conditions identical with those for **11**, reaction 2 for (*R*)-**13** afforded the corresponding epoxide **14** *in the threo configuration only* (88% isolated yield, entry 18). To our knowledge, this is the first epoxidation of protected α-amino alkenes catalyzed by a metal complex.

Catalyst Stability and Reuse. The covalent attachment of **3** to the polymer support indeed makes the resulting supported ruthenium porphyrins **3**-MPR a highly stable catalyst for reaction 2. Under the conditions denoted in Table 1, the catalyst **3a**-MPR was consecutively reused four times without detectable catalyst leaching or a significant loss of epoxide yield.[24] In contrast, the previously reported catalyst **2**-MCM-41 lost about half its original activity after being reused just two times.[5b] With a **3** loading as low as 0.17 wt %, the catalyst **3b**-MPR is still

(12) Groves and co-worker first examined the catalytic behavior of an iron porphyrin toward the epoxidation of a cyclic α,*β*-unsaturated ketone (cyclohex-2-en-1-one) with iodosylbenzene, and observed no activity (see ref 2a). Thereafter, Hirobe and co-workers (ref 6c) demonstrated that the Cl_2pyNO oxidation of *l*-carvone, a cyclic α,*β*-unsaturated ketone with an extra terminal alkene group, catalyzed by a dioxoruthenium(VI) sterically encumbered porphyrin resulted in epoxidation of only the terminal alkene group without affecting the α,*β*-unsaturated ketone moiety.

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(20) (a) Pegorier, L.; Haddad, M.; Larcheveque, M. *Synlett* **1996**, 585. (b) Castejón, P.; Moyano, A.; Pericàs, M. A.; Riera, A. *Tetrahedron* **1996**, *52*, 7063. (c) Aguilar, N.; Moyano, A.; Pericàs, M. A.; Riera, A. *Tetrahedron Lett*. **1999**, *40*, 3913.

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(22) (a) Mitsuya, H.; Yarchoan, R.; Broder, S. *Science* **1990**, *249*, 1533. (b) Askin, D.; Wallace, M. A.; Vacca, J. P.; Reamer, R. A.; Volante, R. P.; Shinkai, I. *J. Org. Chem*. **1992**, *57*, 2771. (c) Thompson, W. J.; Ghosh, A. K.; Holloway, M. K.; Lee, H. Y.; Munson, P. M.; Schwering, J. E.; Wai, J.; Darke, P. L.; Zugay, J.; Emini, E. A.; Schleif, W. A.; Huff, J. R.; Anderson, P. S. *J. Am. Chem. Soc*. **1993**, *115*, 801. (d) Bennett, F.; Patel, N. M.; Girijavallabhan, V. M.; Ganguly, A. K. *Synlett* **1993**, 703. (e) Sham, H. L.; Betebenner, D. A.; Zhao, C.; Wideburg, N. E.; Saldivar, A.; Kempf, D. J.; Plattner, J. J.; Norbeck, D. W. *J. Chem. Soc., Chem. Commun*. **1993**, 1052. (f) Parkes, K. E. B.; Bushnell, D. J.; Crackett, P. H.; Dunsdon, S. J.; Freeman, A. C.; Gunn, M. P.; Hopkins, R. A.; Lambert, R. W.; Martin, J. A.; Merrett, J. H.; Redshaw, S.; Spurden, W. C.; Thomas, G. J. *J. Org. Chem*. **1994**, *59*, 3656. (g) Castejón, P.; Pastó, M.; Moyano, A.; Pericàs, M. A.; Riera, A. *Tetrahedron Lett*. **1995**, *36*, 3019. (h) Beaulieu, P. L.; Wernic, D. *J. Org. Chem*. **1996**, *61*, 3635.

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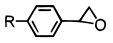
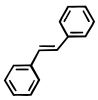
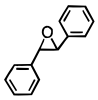
(24) The first run gave styrene epoxide in 96% yield (entry 1 in Table 1). After the catalyst had been reused four times, its **3** loading was determined to be 8.5 wt %. The epoxide yields for the 2nd, 3rd, 4th, and 5th runs were 93, 90, 92, and 91%, respectively.

Table 2. Alkene Epoxidation with Cl_2pyNO Catalyzed by **3b**-MPR[a]

Entry	Substrate	Product		Yield (%)[b]	Turnovers
1				88	1.8×10^4
2			R=H	68	9.5×10^3
3			F	78	8.3×10^3
4			Cl	71	8.7×10^3
5			Br	66	8.0×10^3
6				77	1.2×10^4
7				70	4.8×10^3
8				65	2.3×10^3

[a] All reactions were performed in benzene at 50 °C for 48 h with a catalyst:oxidant:substrate molar ratio of 1:30000:43000. [b] Determined by GC or ^{1}H NMR based on the amount of Cl_2py formed.

efficient in catalyzing alkene epoxidation with Cl_2pyNO, as shown in Table 2. The catalyst turnovers are very high (up to 1.8×10^4). However, the epoxide yields are lower than those obtained by employing catalyst **3a**-MPR (cf. Table 1). For the epoxidation of styrene, consecutively reusing **3b**-MPR nine times, under conditions identical with those denoted in Table 2 except for a shorter reaction time (24 h), revealed no detectable catalyst leaching,[25] with total turnovers reaching 3.0×10^4.

Conclusion

(i) Treatments of carbonyl ruthenium(II) 5,10,15-tris(4-R-phenyl)-20-(4-hydroxyphenyl)porphyrins (R = Cl, **3**; Me, **4**) with Merrifield's peptide resin (MPR) in DMF at 80 °C for 4 h result in the covalent attachment of **3** and **4** to the polymer matrix.

(ii) The polymer-supported ruthenium porphyrin **3a**-MPR with **3** loading of 8.6 wt % is an efficient catalyst for epoxidation of both electron-rich and -deficient alkenes, including 1,5-cyclooctadiene, *trans*-stilbene, α,*β*-unsaturated ketones, conjugated enyne, glycal, and protected α-amino alkene, as well as common unfunctionalized alkenes such as styrenes and norbornene. Prior to this work, no metalloporphyrins have been reported to be active catalysts for Cl_2pyNO or PhIO epoxidation of α,*β*-unsaturated ketones.

(iii) Unusual selectivities are observed in the epoxidations of (a) 1,5-cyclooctadiene: only the corresponding bisepoxide is detected, contrary to the selective monoepoxide formation previously reported for epoxidation of the same alkene catalyzed by a molybdenum porphyrin; (b) *cis*-1-phenyl-3-penten-1-yne: the epoxides obtained feature a cis:trans ratio of 13:1, much higher than the ratio of 1:2 reported for manganese−salen catalysts; and (c) 3,4,6-tri-*O*-acetyl-D-glucal, and (*R*)-2-(Boc-amino)-1-phenylbut-3-ene: complete diastereoselectivity is obtained, in contrast to the corresponding epoxidation catalyzed by a ruthenium porphyrin immobilized onto surface-modified MCM-41 and stoichiometric epoxidation by *m*-CPBA, respectively.

(iv) The catalysts **3**-MPR are robust toward the epoxidation reactions. With styrene as substrate, consecutively reusing the catalysts **3a**-MPR and **3b**-MPR (**3** loading: 0.17 wt %) four and nine times, respectively, results in no detectable catalyst leaching, and in the former case reveals no significant decrease in epoxide yield. Turnovers as high as 3.0×10^4 can be obtained by employing the catalyst **3b**-MPR.

Experimental Section

General. Merrifield's peptide resin (Aldrich, 2% cross-linked, 200−400 mesh, ~2 mmol Cl/g), $Ru_3(CO)_{12}$ (Strem), and alkene **11** (Aldrich) were used as received. 1,2-Dihydronaphthalene and norbornene were purified by sublimation. Alkene (*R*)-**13** was prepared by a literature method.[23a] The other alkenes, all liquid compounds of the highest quality available from commercial vendors, were purified by passing through a column of activated alumina before use. 2,6-Dichloropyridine *N*-oxide was prepared by Rousseau's method.[26] 5,10,15-Tris(4-R-phenyl)-20-(4-hydroxyphenyl)porphyrins (R = Cl, Me) were synthesized according to the reported procedures.[10] All solvents were of AR grade. ^{1}H NMR spectra were measured on a Bruker DPX 300 spectrometer (300 MHz) by using tetramethylsilane (TMS) as an internal standard, with the chemical shifts relative to TMS. Infrared spectra (KBr pellets) were recorded on a Bio-Rad FTS-7 FT-IR spectrometer and Raman spectra on a Bio-Rad FT-Raman laser spectrometer. UV−visible spectra were measured on a Milton Roy Spectronic 3000 diode-array spectrophotometer. Gas chromatography was performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a flame ionization detector and a 3396 Series II integrator. The ruthenium contents in **3**- and **4**-MPR were determined on a Perkin-Elmer 3110 flame atomic absorption spectrometer. Elemental analyses were performed by the Institute of Chemistry, the Chinese Academy of Sciences.

Preparation of Ruthenium Porphyrins 3 and 4. A mixture of $Ru_3(CO)_{12}$ (200 mg) and the corresponding free base porphyrin (200 mg) in Decalin (50 mL) was refluxed under nitrogen for 24 h. The resulting red solution was loaded on an alumina column. Decalin and some other impurities were removed by using hexane as the eluent. The brick red band containing the desired product was then eluted with dichloromethane and collected. Removal of the solvent followed by recrystallization of the residual solid from dichloromethane/*n*-hexane (1:6 v/v) afforded complex **3** or **4** as red purple crystals.

3: Yield: 80%. UV/vis ($CHCl_3$): λ_{max} 418 (Soret), 530 nm. IR: ν(CO) 1941 cm^{-1}. FAB-MS: *m*/*z* 862 (M^+), 834 ([M − CO]$^+$). ^{1}H NMR ($CDCl_3$): δ 8.69 (s, 8H), 8.09 (m, 6H), 8.00 (m, 2H), 7.72 (m, 6H), 7.15 (m, 2H). Anal. Calcd for $C_{45}H_{25}Cl_3N_4O_2Ru \cdot 2H_2O$: C, 60.24; H, 3.26; N, 6.24. Found: C, 60.19; H, 3.38; N, 6.02.

4: Yield: 86%. UV/vis ($CHCl_3$): λ_{max} 416 (Soret), 530 nm. IR: ν(CO) 1942 cm^{-1}. FAB-MS: *m*/*z* 800 (M^+), 772 ([M − CO]$^+$). ^{1}H NMR ($CDCl_3$): δ 8.72 (s, 8H), 8.03 (m, 8H), 7.53 (m, 6H), 7.02 (m, 2H), 2.69 (s, 9H). Anal. Calcd for $C_{48}H_{34}N_4O_2Ru \cdot 2H_2O$: C, 68.97; H, 4.58; N, 6.70. Found: C, 68.76; H, 4.52; N, 6.30.

Preparation of Polymer-Supported Ruthenium Porphyrin Catalysts 3- and 4-MPR. **A Typical Procedure.** To a solution of **3** (0.1 mmol) in DMF (30 mL) were added Merrifield's peptide resin (1.0 g) and anhydrous potassium carbonate (0.5 g). The mixture was vigorously stirred at 80 °C for 4 h under a nitrogen atmosphere. After cooling, the red resin was collected by filtration, washed *thoroughly* with water, ethanol, and chloroform, and dried in vacuo at room temperature for several hours. This procedure gave the catalyst **3a**-MPR. The catalysts **3b**- and **4**-MPR were prepared in a similar manner by using a smaller amount of **3** and **4** (both 2 μmol), respectively. The contents of **3** or **4** in **3**- or **4**-MPR were calculated from the ruthenium contents in the heterogenized catalysts determined by atomic absorption spectroscopy.

3a-MPR: IR: ν(CO) 1944 cm^{-1}. Raman: 1611, 1548, 1366, 1239, 411 cm^{-1} (bands associated with the attached **3**; for comparison, these bands appear at 1612, 1548, 1368, 1234, 412 cm^{-1} in the Raman spectrum of **3**). **3b-MPR:** IR: ν(CO) 1946 cm^{-1}. **4-MPR:** IR: ν(CO) 1947 cm^{-1}.

(25) After each run, the loading of **3** in the recovered **3b**-MPR was determined, which remained unchanged within the experimental error. However, there was a considerable drop of the epoxide yield in the second run. For the remaining runs, the epoxide yield became fairly stable.

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Procedure for Cl_2pyNO Epoxidation of Alkenes Catalyzed by 3a-MPR. All the epoxidation reactions were carried out in a sealed vial or flask under nitrogen. The products were identified by GC in the cases where the corresponding authentic samples were available, or by comparison with the previously reported ^{1}H NMR spectral data in the other cases. Product quantification was made through GC or NMR measurements in the presence of appropriate internal standards.

(i) Alkenes 11 and (*R*)-13. A mixture of alkene (0.60 mmol), Cl_2pyNO (0.61 mmol), and **3a**-MPR (10 mg) in benzene (4 mL) was stirred at 40 °C. When the reaction was complete, as revealed by TLC analysis, the mixture was filtered, and the filtrate was evaporated in vacuo to remove the solvent. The residue was then purified by column chromatography. In the case of **11**, the colorless oil obtained was stirred with anhydrous methanol at room temperature under nitrogen until the methanolysis was complete (monitored by TLC). Removal of methanol followed by chromatography gave a white solid in 56% yield (based on starting alkene **11**), whose ^{1}H NMR spectrum is characteristic of pure methyl 3,4,6-tri-*O*-acetyl-β-D-glucopyranoside.[27] This revealed that the epoxidation product of **11** is α-**12** (notice that the methanolysis of α-**12** would result in an inversion of configuration[5b,19]). For alkene (*R*)-**13**, pure epoxide product was obtained as a colorless oil in 88% yield (TLC, silica gel, *n*-hexane/ether (2:1 v/v), $R_f = 0.35$). The spectral data of the oil are identical with those of the enantiomer of *threo*-**14** reported in the literature.[28]

(27) Methyl 3,4,6-tri-*O*-acetyl-β-D-glucopyranoside shows its methoxy proton resonances at δ 3.58 ppm, which is considerably different from the corresponding resonances (δ 3.44 ppm) of its α counterpart (see ref 5b).

(ii) Other Alkenes. A mixture of alkene (0.80 mmol), Cl_2pyNO (0.70 mmol), and **3a**-MPR (5 mg) in benzene (4 mL) was stirred for 24 h at room temperature. After filtration, the filtrate was analyzed by GC or ^{1}H NMR spectroscopy.

Procedure for Cl_2pyNO Epoxidation of Alkenes Catalyzed by 3b- or 4-MPR. The procedure is the same as that for the corresponding alkene epoxidation catalyzed by **3a**-MPR, except that a mixture of alkene (0.86 mmol), Cl_2pyNO (0.60 mmol), and **3b**- or **4**-MPR (10 mg) was used and stirred at 50 °C for 48 h followed by cooling the mixture to room temperature.

Reuse of Catalyst 3a- or 3b-MPR for Epoxidation of Styrene. At the end of the epoxidation reaction, the catalyst was recovered by filtration and briefly dried under reduced pressure. In all cases, the filtrate was colorless, and the UV/vis spectrum revealed the absence of porphyrin species. The epoxidation reaction was repeated by employing the recovered catalyst, fresh styrene, and Cl_2pyNO under the same conditions.

Acknowledgment. This work was supported by The University of Hong Kong, the Hong Kong University Foundation, and the Hong Kong Research Grants Council.

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(28) The corresponding *erythro*-epoxide was not detected (for identification of the *threo*- and *erythro*-epoxide by means of ^{1}H NMR spectroscopy, see: Evans, B. E.; Rittle, K. E.; Homnick, C. F.; Springer, J. P.; Hirshfield, J.; Veber, D. F. *J. Org. Chem.* **1985**, *50*, 4615).