Dendrimer-Metalloporphyrins: Synthesis and Catalysis

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Abstract: A new class of sterically hindered dendrimer-metalloporphyrins was synthesized for use as shape-selective oxidation catalysts. A series of oxidatively robust poly(phenylesters) dendrimers were prepared through a convergent synthesis. Monodendrons were appended to the *meta*-positions of the 5,10,15,20-tetrakis(3′,5′-hydroxyphenyl)-porphinatomanganese(III) chloride to obtain a sterically protected metal center. These complexes have been examined as regioselective oxidation catalysts for both intra- and intermolecular cases. Epoxidation of nonconjugated dienes and alkene mixtures of 1-alkene and cyclooctene catalyzed by dendrimer-metalloporphyrins has been carried out using iodosylbenzene as the oxygen donor. Significantly greater regioselectivity is observed with the dendrimer-metalloporphyrins, relative to the corresponding parent, 5,10,15,20-tetraphenylporphyrinatomanganese(III) cation. To examine the extent of steric crowding around the porphyrin from the dendrimers, molecular modeling studies were performed on these dendrimer-porphyrins. Although the top access is extremely limited in the dendrimer-metalloporphyrins, a significant side opening permits substrate entrance and limits the regioselectivity that can be achieved with *meta*-substitution of a tetraphenylporphyrin.

Introduction

Synthesis of dendritic polymers are of considerable interest owing to their unique physical and chemical properties.[1] Encapsulation of functional or catalytic sites into the interior of dendrimers remains an important goal. Recent studies include the appendage of metal redox centers to the periphery of a dendrimer, which impart some regiospecific catalytic properties,[2] and incorporation of porphyrins into the interior of ether-based dendrimers, which have unusual photophysical[3] and electrochemical redox[4] behavior. Introduction of bulky dendritic polymers at the peripheral positions of a metalloporphyrin results in steric protection of the metal center and should provide for regio- and shape-selective catalysis. Previous dendrimer-porphyrins, however, are very susceptible to oxidative degradation. Herein, we report the first synthesis of oxidatively robust dendrimer-metalloporphyrins and their use as regioselective oxidation catalysts.

A variety of high-valent metalloporphyrins have been employed as catalysts for the oxidation of organic substrates.[5] The shape-selectivity of the high-valent metalloporphyrin catalyst is strongly influenced by the extent of steric crowding present at the faces of the porphyrin. A wide range of sterically hindered metalloporphyrins[6] have been employed for regio- or shape-selective alkene epoxidation or alkane hydroxylation. Of these, the bis-pocket porphyrin (5,10,15,20-tetrakis(2′,4′,6′-triphenylphenyl)porphyrin) has been the most sterically hindered

porphyrin previously reported.[6abf] The synthesis of such systems, however, is difficult and generally proceeds in very low yield.

The present study presents a facile, *convergent* synthesis of sterically hindered porphyrins by attaching polyester dendrimers to the periphery of a porphyrin core. Bulky cascade polyester dendrimers (G1 and G2 in Scheme 1) were employed to determine the effect of dendrimer size on the substrate selectivity. The presence of *tert*-butyl groups at the exterior positions of the dendrimer increase steric hindrance and enhance solubility, while maintaining stability toward oxidative degradation.

Experimental Section

Materials. 5,10,15,20-Tetrakis(3′,5′-dihydroxyphenyl)porphyrin,[3] $H_2(3′,5′\text{-OHPh})P$, and its manganese derivative,[7] $Mn(T(3′,5′\text{-OHPh})P)$-(Cl), were synthesized using literature procedures. Majority of the alkenes purchased from Aldrich were of high purity and used without further purification. 3,5-Di-*tert*-butyl benzoic acid and 3,5-dihydroxy benzoic acid were obtained from Aldrich and were used as received. All the solvents employed were of high purity and were distilled before use. Tetrahydrofuran obtained from Fisher Scientific was distilled from sodium/benzophenone under nitrogen before use. Dichloromethane was distilled from CaH_2 under N_2. Dicyclohexylcarbodiimide (DCC) obtained from Aldrich was used as received. 4-(Dimethylamino)-pyridinium 4-toluenesulfonate (DPTS) was synthesized using reported procedure.[8]

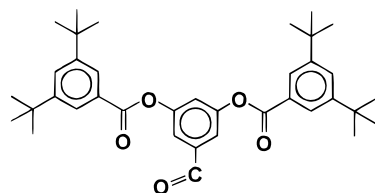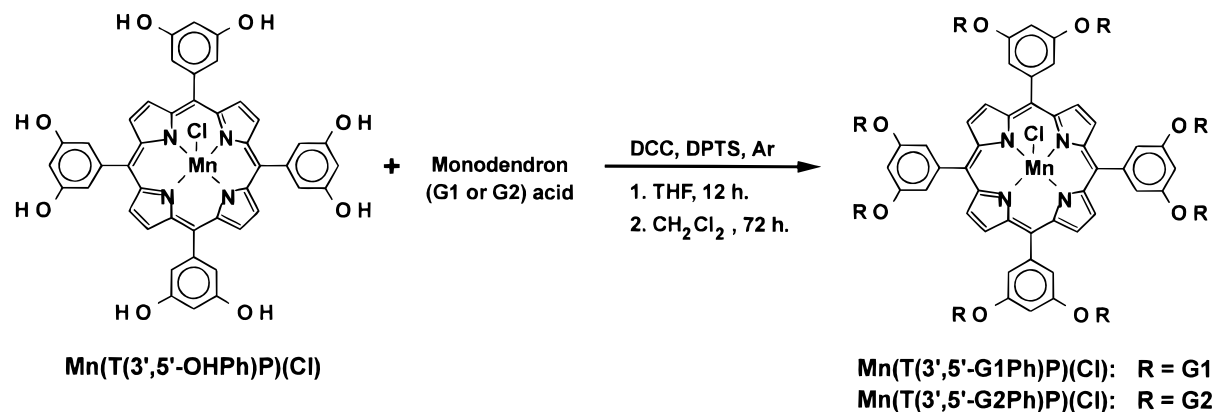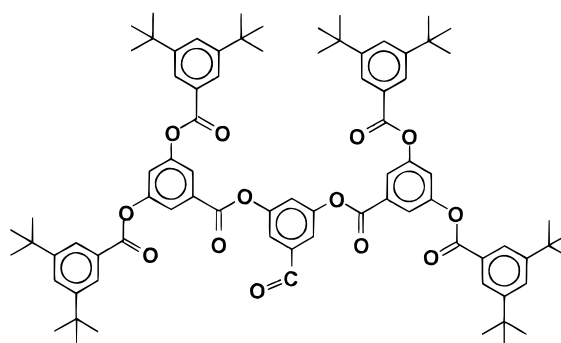[⊗] Abstract published in *Advance ACS Abstracts,* June 1, 1996.

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Scheme 1. Synthesis of Manganese(III) Complexes of Dendrimer-Porphyrins and the Molecular Structures of the Monodendrons

Mn(T(3',5'-OHPh)P)(Cl)

DCC, DPTS, Ar
1. THF, 12 h.
2. CH$_2$Cl$_2$, 72 h.

Mn(T(3',5'-G1Ph)P)(Cl): R = G1
Mn(T(3',5'-G2Ph)P)(Cl): R = G2

First Generation Monodendron, G1

Second Generation Monodendron, G2

Instrumentation. UV−vis absorption spectral measurements were performed on a Hitachi UV 3300 spectrophotometer. The epoxidation products were analyzed with a Varian GL 3700 series capillary gas chromatograph and a Hewlett-Packard GCMS. Computer modeling studies were performed on a Silicon Graphics Indigo 2² work station using Quanta and Charmm software packages. Mass spectra were obtained on a Fisons/VG TofSpec mass spectrometer.

Synthesis. Cascade dendrimers: The first generation (G1) and second generation (G2) dendrimers (cf. Scheme 1) were prepared using literature procedures,[9] with the minor modification of the presence of *tert*-butyl groups at the periphery of the dendrimer to provide extra steric bulk.

Dendrimer-Porphyrin Mn(III) Complexes. These complexes were synthesized by direct DCC coupling reaction[8] of G1-acid or G2-acid with Mn(T(3′,5′-OHPh)P)(Cl) using DPTS as the catalyst. Synthesis was performed in two steps: first in THF, which was removed under reduced pressure, and followed by redissolution and further reaction in CH$_2$Cl$_2$. This was essential due to the low solubility of Mn(T(3′,5′-OHPh)P)(Cl) in CH$_2$Cl$_2$ and the rate dependence of DCC coupling reactions on the solvent employed.[10]

Synthesis of Mn(T(3′,5′-G1Ph)P)(Cl) was performed under an argon atmosphere in two steps. Step 1: MnT(3′,5′-OHPh)P(Cl) (0.004 g, 0.005 mM), dendrimer (G1) (0.030 g, 0.05 mM), and DPTS (0.047 g, 0.16 mM) were dissolved in freshly distilled THF (10 mL). To this, DCC (0.123 g, 0.6 mM) in 1 mL of THF was added, and the solution was stirred under argon for 12 h. At the end of this period, the reaction mixture was filtered, and the solvent was removed under reduced pressure. Step 2: The residue obtained from step 1 was redissolved in CH$_2$Cl$_2$ (3 mL), and excess DCC and catalytic amounts of DPTS were added; the reaction was allowed to continue for a period of 72 h. The reaction mixture was then evaporated to dryness to obtain a green oily residue. The dendrimer-metalloporphyrin complex was obtained

by extraction with pentane (yield: 55%). Similar procedure was employed for the condensation of G2 dendrimer with Mn(T(3′,5′-OHPh)P)(Cl).

HPLC analyses of the dendrimer-porphyrin complexes were performed to demonstrate purity, using a normal phase silica gel column with 30% THF in CH$_2$Cl$_2$ as the eluent. UV−vis spectrum of manganese porphyrins were obtained in THF: λ_{max} (nm), Mn(T(3′,5′-OHPh)P)(Cl)]: 374, 395, 479, 523, 584, and 623 nm; Mn(T(3,5-G1Ph)P)(Cl)]: 370, 390 (sh), 474, 520, 580, and 620 nm; Mn(T(3′,5′-G2Ph)P)(Cl): 368, 386 (sh), 476, 521, 576, and 622 nm. Low resolution matrix assisted laser desorption ionization time of flight mass spectral technique (MALDI-TOF) was very useful in characterization of the manganese complex of these dendrimer-porphyrins. MALDI-TOF mass spectra of the manganese porphyrin dendrimer complexes were obtained using a 2-(4-hydroxyphenylazo)benzoic acid (HABA) matrix. MALDI-TOF mass spectrum of the Mn(T(3′,5′-G1Ph)P)(Cl) shows exclusively the molecular ion peak at [M − Cl]⁺ (m/z) 5344 (calcd [M − Cl] 5346.2), and Mn(T(3′,5′-G2Ph)P)(Cl) exhibit molecular ion peak [M − Cl]⁺ at 10 980 (calcd 10 985). In the latter, two minor peaks were observed at (m/z) 9724 and 8462 possibly due to successive loss of one and two dendrimer (G2) units from the parent molecular ion (calcd m/z 9694 and 8437, respectively).

Epoxidation Reactions. Epoxidations were performed under argon using iodosylbenzene as the oxygen donor. In a typical experiment, iodosylbenzene (10 μmol) and alkene (500 μmol) were added to 1 mL of CH$_2$Cl$_2$ containing the manganese porphyrin catalyst (1 μmol). The solution was vigorously stirred under argon for 30 min. At the end of this period, an internal standard (decane) was added, and the products were analyzed by GC and GCMS. The obtained yields of epoxides were greater than 80% based on the amount of iodosylbenzene employed. Standard epoxides were purchased from Aldrich or synthesized by using *m*-chloroperbenzoic acid as the oxidant and were analyzed by GC and GCMS.

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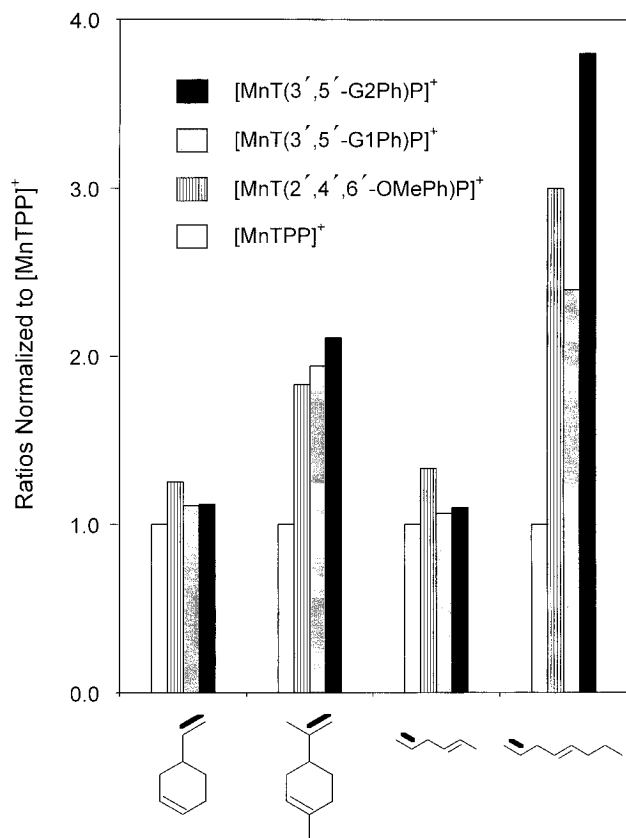(10) DeTar, D. F.; Silverstein, R. *J. Am. Chem. Soc.* **1966**, *88*, 1013.

Figure 1. The epoxide product distribution, given as the epoxide fraction formed from the most sterically accessible double bond of the substrates, for each metalloporphyrin catalyst compared to [Mn(TPP)]$^+$. The most sterically accessible double bond is indicated by heavy lines for each case. Errors are estimated at ±5% relative. Data for [Mn(T(2′4′6′-OMePh)P)]$^+$ for comparison were taken from ref 6b.

Results and Discussion

Dendrimer-metalloporphyrins were synthesized by appending the dendrimers (G1 or G2) at the *meta*-phenyl positions of the Mn(T(3′,5′-OHPh)P)(Cl) using DCC coupling reaction in the presence of DPTS as the catalyst (Scheme 1). All the synthesized dendrimer-porphyrins were green viscous oils and were obtained in good yields (50–60%). These complexes were found to be very soluble even in *n*-alkanes, but less soluble in more polar solvents. The integrity of the manganese-porphyrin core in these complexes was confirmed by UV–vis spectroscopy, which exhibit electronic absorption spectrum similar to, but blue-shifted from, that of Mn(T(3′,5′-OHPh)P)(Cl). Purity of the complexes was confirmed by high-performance liquid chromatography (HPLC) and by low resolution matrix assisted laser desorption ionization time of flight mass spectroscopy (MALDI-TOF) mass spectral techniques.

Epoxidation of olefins was performed with these dendrimer-metalloporphyrins using iodosylbenzene as the oxygen donor. To demonstrate the extent of steric hindrance in the dendrimer-metalloporphyrins (G1 and G2), both intra- and intermolecular regioselectivity were examined using catalytic epoxidation of several nonconjugated dienes and of 1:1 intermolecular (1-alkene to *cis*-cyclooctene) mixtures of various alkenes with different shapes and sizes. Control epoxidation reactions were carried out with the unsubstituted Mn(TPP)(Cl) and were found to be similar to those of previous reports.[6b,h] Representative data for the epoxidation of series of nonconjugated dienes are shown in Figure 1.

The dendrimer-metalloporphyrin complexes exhibit considerable selectivity compared to Mn(TPP)(Cl). As one would expect
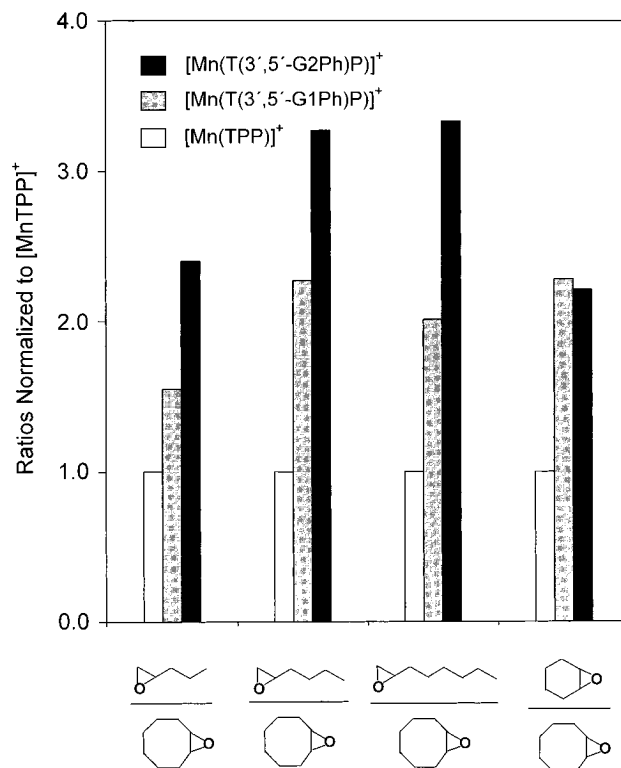

Figure 2. Epoxidation results for the intermolecular mixture of alkenes. The ratios of the epoxides are normalized with respect to corresponding [Mn(TPP)]$^+$ values. Errors are estimated at ±5% relative.

for intramolecular selectivity with sterically hindered catalysts, the least hindered (i.e., external) double bond in dienes undergoes epoxidation more readily than the more hindered (i.e., internal) double bond. For dienes, dendrimer-metalloporphyrins exhibit selectivity similar to that of substantially hindered Mn(T(2′,4′,6′-OMePh)P)(OAc). Figure 2 shows the epoxidation data for intermolecular mixtures of alkenes. For intermolecular selectivity with an unhindered catalyst, one would expect greater reactivity towards the more electron rich *cis*-cyclooctene than toward 1-alkenes. For the 1:1 intermolecular alkene mixtures, the dendrimer-metalloporphyrins show two- to three-fold higher selectivity relative to Mn(TPP)(Cl). Selectivity increases slightly from 1-pentene to 1-hexene to 1-octene. Selectivity also increases from Mn(T(3′,5′-G1Ph)P)(Cl) to Mn(T(3′,5′-G2Ph)P)(Cl) for the intermolecular alkene mixture, as expected due to the increase in dendrimer size from G1 to G2. The higher selectivity of the dendrimer-metalloporphyrin complex are mainly due to the steric influence of the bulky dendrimers at the periphery of the Mn(III)-porphyrin catalyst rather than any electronic factors.

The turnover numbers (i.e., mol product/mol metalloporphyrin/s) obtained for dendrimer-porphyrin complexes (2–4 s^{-1}) are similar to that of Mn(TPP)(Cl) (3–4 s^{-1}). In addition, excellent oxidative stability was observed for dendrimer-metalloporphyrins: under conditions used for epoxidation, after 1000 turnovers (of oxidant), less than 10% degradation had occurred (based on UV–vis spectroscopy).

The dendrimer-porphyrin complexes were compared to the bis-pocket porphyrin (5,10,15,20-tetrakis(2′,4′,6′-triphenyl-phenyl)porphyrin) to provide an interesting contrast in the effects of top versus side access to the metal site. Although reasonable shape selectivity is observed for our dendrimer-metalloporphyrins, they are still well surpassed by the bis-pocket porphyrin complexes, which have bulky (phenyl) substitution of the *ortho* positions of the *meso*-phenyl rings. In order to examine the differences between these systems, molecular modeling studies
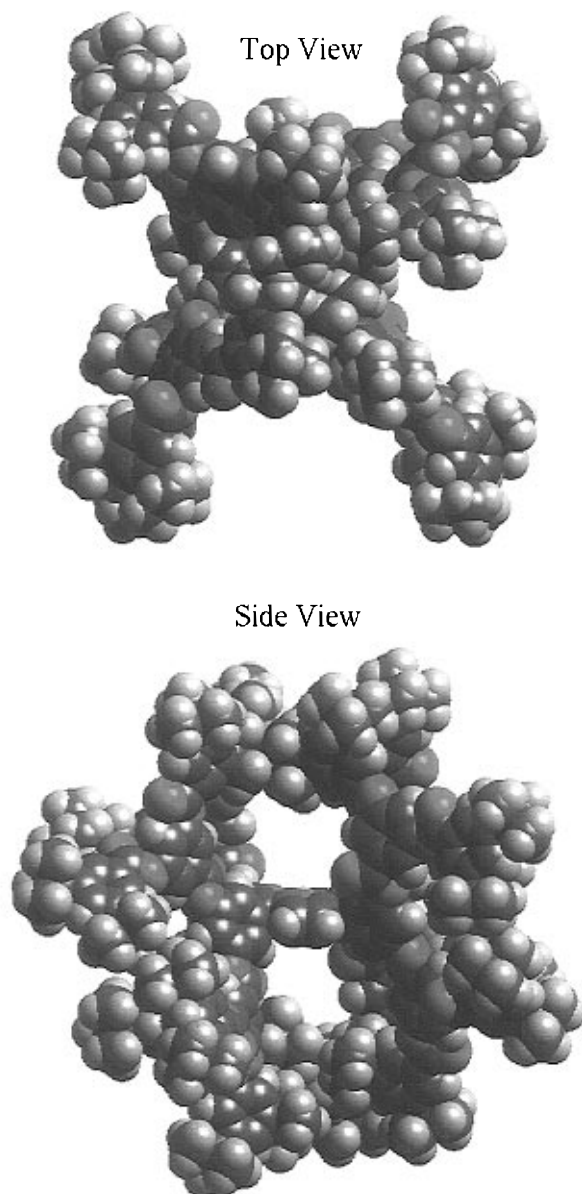
Top View

Side View

Figure 3. Molecular models of a dendrimer-porphyrin, $H_2T(3',5'$-G1Ph)P. Full van der Waals radii are shown. The top view shows complete blockage of the porphyrin face; the side view reveals a 10 Å opening for $H_2T(3',5'$-G1Ph)P.

were performed on the metal-free dendrimer-porphyrins, as shown in Figure 3. From the top view, it would appear that the dendrimer-porphyrin is much more sterically crowded than the bis-pocket porphyrin, which shows a accessible cavity with a top entrance size of ≈4 Å. In contrast, however, the side

view (along the porphyrin plane) of the dendrimer-porphyrins show a side entrance opening of 10 Å and 7 Å (van der Waals surface to surface) for G1 and G2 porphyrins, respectively, whereas the bis-pocket porphyrin has essentially no side access at all. Docking studies on dendrimer-porphyrins with alkenes (1-alkenes and *cis*-cyclooctene) indicated alkenes can enter the pocket with less steric constraints relative to extremely hindered bis-pocket porphyrin. The observed selectivities are thus fully consistent with the expectation that the approach of the alkene must be to the side of the oxo-mangenese intermediate.[11]

Conclusions

We have prepared a new class of oxidatively robust dendrimer-metalloporphyrin for use as sterically hindered, shape-selective oxidation catalysts. Using a convergent synthesis, a series of poly(phenylester) dendrimers were prepared by the attachment of monodendrons to the *meta*-positions of the 5,10,15,20-tetrakis(3′,5′-dihydroxyphenyl)porphinatomanganese-(III) chloride, thus sterically protecting the metal center. These complexes have been examined as regioselective epoxidation catalysts, for both intramolecular and intermolecular selectivities. While these dendrimer-porphyrins do show significantly greater regioselectivity than the corresponding unhindered parent metalloporphyrin, the selectivities are not as high as those achieved with complexes of bis-pocket porphyrin, (5,10,15,20-tetrakis-(2′,4′,6′-triphenylphenylporphyrin)).

To rationalize this result, the extent of steric crowding around the porphyrin from the dendrimers was examined by molecular modeling. The bis-pocket and dendrimer systems make an interesting comparison. In the former, side-access is completely blocked, but top access to the putative metal oxo intermediate is available, while in the latter it is the reverse. The significant side opening of these dendrimer-metalloporphyrins limits the extent of regioselectivity that can be achieved with *meta*-substitution of a tetraphenylporphyrin. The placement of the dendrimer substituent on the *meta* position is desirable for ease of synthesis; attempts at esterification of *ortho*-substituted porphyrins has not yielded complete octa-ester formation. By use of amide linkages, *ortho* linkage of monodendrons on the porphyrin periphery may become possible, and such attempts are now being made.

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