Homogeneous dihydroxylation of olefins catalyzed by a recyclable OsO_4^{2-} core dendrimer

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ABSTRACT

By employing an osmate (OsO_4^{2-}) core dendrimer as a catalyst, homogeneous dihydroxylation reactions proceeded rapidly, and the dendritic osmium catalyst was efficiently recycled by reprecipitation.
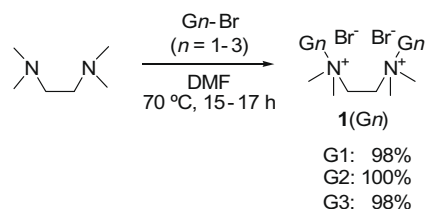
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Osmium-catalyzed dihydroxylation of olefins is one of the most useful transformations for the preparation of vicinal diols.[1] Although these reactions have had widespread application in organic synthesis, few fruitful industrial applications have been identified due to the high cost performance, toxicity, and possible contamination of toxic osmium in the final product.[2] One of the most promising solutions to these problems is the immobilization of the catalytic metals to an insoluble matrix. Previously, heterogenization of catalytic osmium by immobilization on various organic and inorganic supports has been successful, but the lower activity and stability of the complex remain as severe problems.[3–5] There are few examples of recyclable homogeneous osmium catalysts with higher activity than those of heterogeneous catalysts.[6]

Dendrimers are fascinating macromolecules due to their unique physical and chemical properties, caused by their well-defined hyperbranched framework.[7] Metallodendrimers, with catalytic sites immobilized on the dendrimer, are particularly useful as synthetic catalysts not only because of their fair solubility but also because of their recyclability by reprecipitation.[8] Presently, metallodendrimers with a catalytic site at the core have received considerable attention due to their unique selectivity and reactivity caused by specific reaction fields constructed by the dendron.[9] Recently, several examples of a positive dendritic effect on chemical yields, which means that the reactivity is enhanced by increasing the generation number of the dendrimer, have been reported by us[10] and by other groups.[11] A few examples of these unique phenomena are thought to be caused by the suppression of the decomposition of catalytic metal within the dendrimer.[10b,11d,12] It was expected that the decomposition of osmium catalyst would be suppressed by the introduction of catalytic osmium at the *core* site of high-generation dendrimer. We wish to report herein the synthesis of a series of novel dendritic supports with a bis(ammonium bromide) core, homogeneous dihydroxylation of olefins cat-

alyzed by the corresponding osmate (OsO_4^{2-}) core dendrimer,[13] and efficient recycling of the dendritic catalyst by reprecipitation.

Novel bis(ammonium bromide) core dendrimers 1(Gn) were readily synthesized as follows (Scheme 1). After the addition of N,N,N′,N′-tetramethylethylenediamine to a N,N-dimethylformamide (DMF) solution of poly(benzyl ether) dendritic bromide Gn–Br[14] (structural formulas of Gn are shown in Figure 1), the reaction mixture was stirred at 70 °C for 15–17 h under an argon atmosphere. In the case of G1, because 1(G1) was precipitated during the reaction, 1(G1) was collected by filtration of the reaction mixture followed by washing with acetone. On the other hand, in the case of G2 and G3, the reaction mixture was evaporated in vacuo, and the residue was purified by column chromatography on silica gel. In all generations, the corresponding bis(ammonium bromide) core dendrimers 1(Gn) were obtained in excellent chemical yields.[15]

Next, novel OsO_4^{2-} core dendrimers were prepared by an ion-exchange procedure, as follows (Table 1). In the case of G1, 1(G1), which has low solubility in water and in most organic solvents, and K_2OsO_4 were vigorously stirred in water to afford 2(G1), which was obtained by filtration of the reaction mixture. In the case of G2 and G3, 1 and K_2OsO_4 were vigorously stirred in water and dendrimer-soluble organic solvent as a two-phase condition, followed by extraction.[15] The Os content of 2(Gn) was determined by ICP-AES. The Os content of 2(G1) was much lower than the calculated value, likely due to the low solubility of

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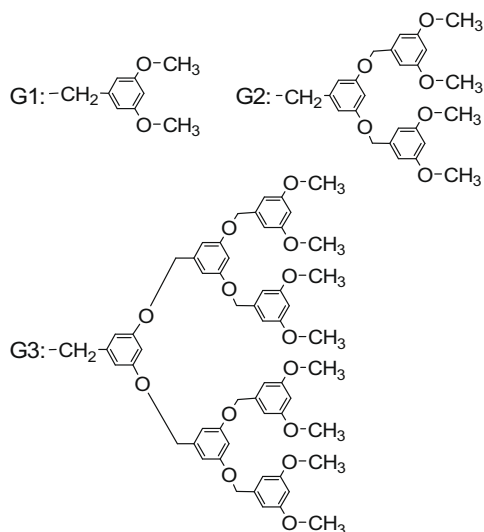 *E-mail address:* k.fujita@aist.go.jp (K. Fujita).

Scheme 1. Synthesis of dendrimer 1(Gn).

Figure 1. Structural formulas of Gn dendrons ($n = 1$–3).

Table 1
Preparation of OsO$_4$$^{2-}$ core dendrimer **2**(Gn)[a]

| Gn	Solvent	Os content[b] of **2**(Gn) (mmol/g)	
		Found	Calcd
G1	H$_2$O	0.36	1.49
G2	H$_2$O–CH$_2$Cl$_2$	0.76	0.82
G3	H$_2$O–toluene	0.22	0.43

[a] Reaction conditions: **1**(Gn), an equimolar amount of K$_2$OsO$_4$, carried out at room temperature for 5 h.
[b] Determined by ICP-AES.

1(G1) in water in the preparation of **2**(G1). In all generations, it was found that the ion-exchange for OsO$_4$$^{2-}$ was incomplete.

We then examined the utility of the dendrimer **2**(Gn) as an osmium catalyst by performing cis-dihydroxylation of olefins (Table 2). By employing 1 mol % of dendritic osmium catalysts **2**(Gn) of various generations, cis-dihydroxylation reactions of trans-β-methylstyrene were carried out by the use of N-methylmor-

Table 2
Cis-dihydroxylation of trans-β-methylstyrene catalyzed by **2**(Gn)[a]
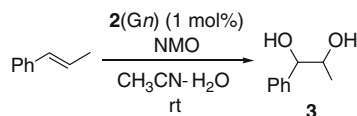
Gn	Yield[b] (%) (Time (h))		
	1st	2nd	3rd
G1	90 (0.5)	97 (2)	43 (14)
G2	97 (0.5)	97 (1)	93 (2)
G3	93 (0.5)	97 (0.5)	96 (0.7)

[a] Reaction conditions: **2**(Gn) (1 mol %), olefin (1 equiv), NMO (1.2 equiv), CH$_3$CN–H$_2$O (4:1, v/v, 0.25 M based on olefin), carried out at room temperature for indicated time.
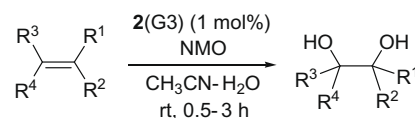[b] Determined by integration of ^{1}H NMR absorptions referred to an internal standard.

pholine N-oxide (NMO) as a re-oxidant in aqueous acetonitrile (CH$_3$CN:H$_2$O = 4:1 (v/v)) at room temperature. After the disappearance of trans-β-methylstyrene, which was monitored by thin-layer chromatography (TLC), a small amount of acetone solution of the evaporated reaction mixture was poured into water. The precipitated dendritic osmium catalysts were recovered and subsequently reused.[16]

In these catalytic conversions, **2**(Gn) was completely dissolved in the reaction mixture, allowing the dihydroxylation reactions to proceed homogeneously to completion in 0.5 h in all generations ("1st" column in Table 2). Next, by carrying out reprecipitation for the catalyst recycling, the recovery of **2** was low in the case of G1 and G2 (ca. 50% and 80% for G1 and G2, respectively). This is likely due to the dendritic catalyst **2**(Gn) with its lower molecular weight, being somewhat dissolved in the water solvent. In contrast, in the case of G3, the catalyst **2**(G3) was recovered nearly quantitatively. The leaching of osmium off the third-generation dendritic backbone, which was determined by ICP-AES, was 1% in each round.

Furthermore, in the case of G3, even the third round of dihydroxylation was completed within 0.7 h with an excellent chemical yield. In contrast, in the case of G1, the third round of dihydroxylation proceeded very slowly to afford **3** in only 43% yield, even when allowed to proceed for 14 h. By the comparison of increases in the reaction time by increasing the recycling number, the increase in the reaction time for G3 (0.5 h→0.7 h) is much smallest in all generations. The relationship between the generation number of **2**(Gn) and increases in the reaction time by increasing the recycling number is one of the positive dendritic effects.[10,11,17,18] To our knowledge, these results are the first to be reported of the dendritic effect on recyclability of a catalyst.

Encouraged by these results, we subsequently performed cis-dihydroxylation of various olefins by employing 1 mol % of the third-generation dendritic osmium catalyst **2**(G3), which was recycled most efficiently in the catalytic system (Table 3). In all cases, the dihydroxylation reactions proceeded smoothly. Especially, in the case of using substituted styrene derivatives, dihydroxylations were completed within 0.5 h (entries 1–4). Dihydroxylations catalyzed by the dendritic osmium catalyst

Table 3
Cis-dihydroxylations of various olefins catalyzed by **2**(G3)[a]

Entry	Olefin	Time (h)	Yield[b] (%)
1	Ph	0.5	86
2	Ph	0.5	92
3	Ph	0.5	86
4	Ph	0.5	90
5	Ph	0.5	81
6	$^nC_8H_{17}$	2	90
7	$^nC_4H_9$ $^nC_4H_9$	3	89
8		1.5	94
9	Ph	1	91

[a] The reaction conditions were the same as in Table 2.
[b] Isolated yield.

Table 4
Catalyst recycling in *cis*-dihydroxylations by use of **2**(G3)[a]

Entry	Olefin	Yield[b] (%)				
		1st	2nd	3rd	4th	5th
1	Ph	86	90	87	88	91
2	Ph	92	93	86	88	93
3	Ph	86	92	89	87	95
4	Ph	90	91	92	88	83
5	Ph	81	90	86	80	89

[a] The reaction conditions were the same as in Table 2. Carried out for 0.5–2 h.
[b] Isolated yield.

2(G3) were more rapid than those previously reported for osmium catalysts due to the homogeneity of **2**(G3).

Finally, the reusability of the catalyst **2**(G3) was examined again using various olefins (Table 4). In these experiments, it was found that the catalyst **2**(G3) could be efficiently recycled up to five times by reprecipitation, and the corresponding diols were consistently obtained in good chemical yields in 0.5–2 h in all cases. Also considering the dendritic effect on recyclability of a catalyst (Table 2), the efficient recycling of **2**(G3) was probably due to the decomposition of the catalytic osmium being suppressed by its inclusion with the dendrimer due to the introduction of OsO_4^{2-} at the *core* site of the dendrimer.

In summary, by performing a homogeneous dihydroxylation reaction in the use of a novel dendritic osmium catalyst, a positive dendritic effect on recyclability of a catalyst was observed. By employing the third-generation dendritic osmium catalyst, the osmium catalyst was efficiently recycled up to five times in the dihydroxylation reactions.

Supplementary data

Characterization data and copies of ^{1}H NMR and ^{13}C NMR spectra of **1**(*Gn*) and typical procedure for the preparation of **2**(*Gn*) are available. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2009.11.126.

References and notes

1. Schröder, M. *Chem. Rev.* **1980**, *80*, 187–213.
2. (a) Hammond, C. R. In *CRC Handbook of Chemistry and Physics*, 81st ed.; Lide, D. R., Ed.; CRC Press: Boca Raton, FL, 2000, p. 4.; (b) Leadbeater, N. E.; Marco, M. *Chem. Rev.* **2002**, *102*, 3217–3274.
3. Immobilization of OsO_4^{2-} by ion-exchange technique: (a) Jun, B.-H.; Kim, J.-H.; Park, J.; Kang, H.; Lee, S.-H.; Lee, Y.-S. *Synlett* **2008**, 2313–2316; (b) Jiang, R.; Kuang, Y.; Sun, X.; Zhang, S. *Acta Chim. Slov.* **2005**, *52*, 467–470; (c) Kim, K. J.; Choi, H. Y.; Hwang, S. H.; Park, Y. S.; Kwueon, E. K.; Choi, D. S.; Song, C. E. *Chem. Commun.* **2005**, 3337–3339; (d) Choudary, B. M.; Jyothi, K.; Kantam, M. L.; Sreedhar, B. *Adv. Synth. Catal.* **2004**, *346*, 45–48; (e) Choudary, B. M.; Chowdari, N. S.; Jyothi, K.; Kantam, M. L. *J. Am. Chem. Soc.* **2002**, *124*, 5341–5349.
4. Microencapsulation of OsO4: (a) Ishida, T.; Akiyama, R.; Kobayashi, S. *Adv. Synth. Catal.* **2005**, *347*, 1189–1192; (b) Ley, S. V.; Ramarao, C.; Lee, A.-L.; Østergaard, N.; Smith, S. C.; Shirley, I. M. *Org. Lett.* **2003**, *5*, 185–187; (c) Nagayama, S.; Endo, M.; Kobayashi, S. *J. Org. Chem.* **1998**, *63*, 6094–6095.
5. (a) Lee, B. S.; Mahajan, S.; Janda, K. D. *Tetrahedron Lett.* **2005**, *46*, 4491–4493; (b) Miao, J. H.; Yang, J.-H.; Chen, L.-Y.; Tu, B.-X.; Huang, M. Y.; Jiang, Y.-Y. *Polym. Adv. Technol.* **2004**, *15*, 221–224; (c) Yang, J. W.; Han, H.; Roh, E. J.; Lee, S.-g.; Song, C. E. *Org. Lett.* **2002**, *4*, 4685–4688; (d) Severeyns, A.; De Vos, D. E.; Fiermans, L.; Verpoort, F.; Grobet, P. J.; Jacobs, P. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 586–589.
6. (a) Jiang, R.; Kuang, Y.; Sun, X.; Zhang, S. *Tetrahedron: Asymmetry* **2004**, *15*, 743–746; (b) Chandrasekhar, S.; Narsihmulu, C.; Sultana, S. S.; Reddy, N. R. *Chem. Commun.* **2003**, 1716–1717; (c) Yao, Q. *Org. Lett.* **2002**, *4*, 2197–2199.
7. (a) *Dendrimers and Other Dendritic Polymers*; Fréchet, J. M. J., Tomalia, D. A., Eds.; John Wiley & Sons: New York, 2001; (b) Newkome, G. R.; Moorefield, C. N.; Vogtle, F. *Dendrimers and Dendrons*; Wiley-VCH: Weinheim, 2001; (c) Chase, P. A.; Gebbink, R. J. M. K.; van Koten, G. *J. Organomet. Chem.* **2004**, *689*, 4016–4054; (d) Fréchet, J. M. J. *J. Polym. Sci.: Part A: Polym. Chem.* **2003**, *41*, 3713–3725.
8. (a) *Dendrimer Catalyst*; Gade, L. H., Ed.; Springer-Verlag: Berlin, Heidelberg, 2006; (b) Méry, D.; Astruc, D. *Coord. Chem. Rev.* **2006**, *250*, 1965–1979; (c) Grayson, S. M.; Fréchet, J. M. J. *Chem. Rev.* **2001**, *101*, 3819–3867; (d) Astruc, D.; Chardac, F. *Chem. Rev.* **2001**, *101*, 2991–3023.
9. Twyman, L. J.; King, A. S. H.; Martin, I. K. *Chem. Soc. Rev.* **2002**, *31*, 69–82.
10. (a) Muraki, T.; Fujita, K.; Kujime, M. *J. Org. Chem.* **2007**, *72*, 7863–7870; (b) Hattori, H.; Fujita, K.; Muraki, T.; Sakaba, A. *Tetrahedron Lett.* **2007**, *48*, 6817–6820; (c) Fujita, K.; Muraki, T.; Hattori, H.; Sakakura, T. *Tetrahedron Lett.* **2006**, *47*, 4831–4843; (d) Muraki, T.; Fujita, K.; Terakado, D. *Synlett* **2006**, 2646–2648.
11. (a) Snelders, D. J. M.; van Koten, G.; Gebbink, R. J. M. K. *J. Am. Chem. Soc.* **2009**, *131*, 11407–11416; (b) Wang, Z.-J.; Deng, G.-J.; Li, Y.; He, Y.-M.; Tang, W.-J.; Fan, Q.-H. *Org. Lett.* **2007**, *9*, 1243–1246; (c) Helms, B.; Liang, C. O.; Hawker, C. J.; Fréchet, J. M. J. *Macromolecules* **2005**, *38*, 5411–5415; (d) Fujihara, T.; Obora, Y.; Tokunaga, M.; Sato, H.; Tsuji, Y. *Chem. Commun.* **2005**, 4526–4528; (e) Zhang, X.; Xu, H.; Dong, Z.; Wang, Y.; Liu, J.; Shen, J. *J. Am. Chem. Soc.* **2004**, *126*, 10556–10557; (f) Fan, Q.-H.; Chen, Y.-M.; Chen, X.-M.; Jiang, D.-Z.; Xi, F.; Chan, A. S. C. *Chem. Commun.* **2000**, 789–790.
12. Iwasawa, T.; Tokunaga, M.; Obora, Y.; Tsuji, Y. *J. Am. Chem. Soc.* **2004**, *126*, 6554–6555.
13. However osmium core dendrimers have been reported previously, their catalytic activity was as low as in the case of heterogeneity: Tang, W.-J.; Yang, N.-F.; Yi, B.; Deng, G.-J.; Huang, Y.-Y.; Fan, Q.-H. *Chem. Commun.* **2004**, 1378–1379.
14. (a) Muraki, T.; Fujita, K.; Oishi, A.; Taguchi, Y. *Polym. J.* **2005**, *37*, 847–853; (b) Tomoyose, Y.; Jiang, D.-L.; Jin, R.-H.; Aida, T.; Yamashita, T.; Horie, K.; Yashima, E.; Okamoto, Y. *Macromolecules* **1996**, *29*, 5236–5238; (c) Hawker, C. J.; Fréchet, J. M. J. *J. Am. Chem. Soc.* **1990**, *112*, 7638–7647.
15. *Selected data*: **1**(G3) White foam; IR (KBr) 3356, 3000, 2937, 2838, 1590, 1429, 1300, 1270, 1205, 1150, 1052, 1009, 834 cm^{-1}; ^{1}H NMR (400 MHz; CDCl$_3$) δ = 6.71 (d, *J* = 1.6 Hz, 4H), 6.67 (d, *J* = 2.0 Hz, 8H), 6.61–6.56 (m, 2H), 6.52 (d, *J* = 2.0 Hz, 16H), 6.51 (t, *J* = 2.0 Hz, 4H), 6.35 (t, *J* = 2.2 Hz, 8H), 4.90 (s, 24H), 4.86 (s, 4H), 4.67 (s, 4H), 3.72 (s, 48H), 3.10 (s, 12H); ^{13}C NMR (100 MHz; CDCl$_3$) δ = 160.9, 160.0, 159.9, 139.1, 138.8, 127.8, 111.9, 106.6, 105.3, 104.7, 101.7, 99.8, 70.0, 67.7, 57.9, 55.4, 49.9; Anal. Calcd for C$_{120}$H$_{134}$Br$_2$N$_2$O$_{28}$: C, 65.15; H, 6.11; N, 1.27; Br, 7.22. Found: C, 64.99; H, 5.93; N, 1.22; Br, 7.08. **2**(G3) Black solid; Os content: 0.22 mmol/g (ICP-AES). The ion-exchange for OsO_4^{2-} was incomplete. The data of IR and elemental analysis are shown below. IR (KBr) 3447, 2961, 2936, 2838, 1457, 1205, 1155, 1052, 832 cm^{-1}; Anal. Found: C, 59.80; H, 5.62; N, 1.13; Os, 4.13.
16. *General procedure*: To a CH$_3$CN–H$_2$O (4:1, v/v) solution (4 mL) of **2**(G3) (0.01 mmol) were added olefin (1 mmol) and *N*-methylmorpholine N-oxide (NMO; 1.2 mmol) successively at room temperature under an argon atmosphere. After stirring the resulting mixture for 0.5–3 h, the dihydroxylation reaction was completed (monitored by TLC or GC). The reaction mixture was evaporated and dissolved in a small amount of acetone. The acetone solution was poured into 6 mL of water to precipitate **2**(G3) as a grayish powder. After centrifugal separation, the aqueous solution was decanted, and the recovered **2**(G3) was reused for subsequent dihydroxylation reactions.
17. Reviews of the dendritic effect: (a) Helms, B.; Fréchet, J. M. J. *Adv. Synth. Catal.* **2006**, *348*, 1125–1148; (b) Chow, H.-F.; Leung, C.-F.; Wang, G.-X.; Yang, Y.-Y. *C.R. Chimie* **2003**, *6*, 735–745.
18. Examples of dendritic effect on selectivity: (a) Benito, J. M.; de Jesús, E.; de la Mata, F. J.; Flores, J. C.; Gómez, R. *Chem. Commun.* **2005**, 5217–5219; (b) Fujita, K.; Muraki, T.; Sakurai, T.; Oishi, A.; Taguchi, Y. *Chem. Lett.* **2005**, *34*, 1180–1181; (c) Ribourdouille, Y.; Engel, G. D.; Plouet, M. R.; Gade, L. H. *Chem. Commun.* **2003**, 1228–1229; (d) Mizugaki, T.; Murata, M.; Ooe, M.; Ebitani, K.; Kaneda, K. *Chem. Commun.* **2002**, 52–53; (e) Bhyrappa, P.; Young, J. K.; Moore, J. S.; Suslick, K. S. *J. Am. Chem. Soc.* **1996**, *118*, 5708–5711.