Synthesis of Water-Soluble Dendritic Phosphine Ligands and Their Application to Hydration of Alkynes in Aqueous Media

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A series of water-soluble dendritic ligands with a phosphine core was synthesized through the coupling of tris(4-hydroxyphenyl)phosphine oxide with poly(benzyl ether) dendron having tri(ethylene glycol) units, followed by reduction. By employing the corresponding water-soluble phosphine–gold(I) dendrimers as a catalyst, the hydration of alkynes proceeded smoothly. Furthermore, by membrane separation based on the nano-order size of the dendritic catalyst, the gold(I) catalyst was recycled without deactivation.

Organic reactions in water are currently of great interest because water is a readily available, economical, safe, and environmentally friendly solvent.[1] To date, various water-soluble ligands have been prepared, and their applications to aqueous media organic syntheses have been reported. Above all, water-soluble phosphine–transition metal catalysts have been widely investigated.[2]

In recent years, organogold compounds as homogeneous catalysts have been widely investigated.[3] Gold catalysts activate the addition of nucleophiles to unsaturated carbon compounds.[4] It has been reported that several phosphine–gold catalysts cause the hydration of alkynes with high efficiency.[5] However, there are few examples of the use of water-soluble phosphine–gold catalysts.[4g,5a]

Dendrimers are fascinating molecules due to their unique physical and chemical properties caused by their well-defined hyperbranched frameworks.[6] From the perspective of their character, immobilization of functional or catalytic sites on dendrimers is one of the important goals. In particular, dendritic catalysts have received considerable attention due to the possibility of catalyst recovery using membrane separation by nanofiltration techniques[7] and due to the alteration of catalyst solubility by peripheral modification.[8]

We have recently synthesized a series of dendritic phosphine core ligands having carboxy groups at the peripheral layer **1**(G*n*[CO_2H]), which is shown in Figure 1. By employing a water-soluble **1**(G*n*[CO_2K])–palladium catalyst, an aqueous media Suzuki–Miyaura reaction was carried out smoothly.[9] However, the dendritic phosphine ligand **1**(G*n*[CO_2K]), which is easily dissolved in water, cannot be utilized under neutral or acidic conditions. We wish to report herein the preparation of a series of water-soluble dendritic phosphines having tri(ethylene glycol) units at the peripheral layer **1**(G*n*[TEG]), hydrations of alkynes, conducted by employing the corresponding water-soluble phosphine–gold(I) catalyst, and the recycling of the higher generation dendritic gold(I) catalyst by membrane separation based on its nano-order size. We were able to successful gold(I) catalyst recycling in hydrations of alkynes without any organic solvent.

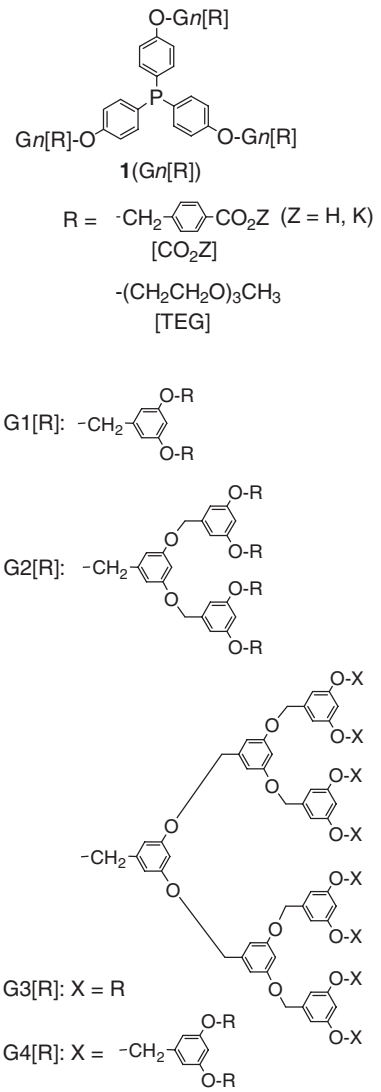

Figure 1. Structural formulas of dendrimer **1**(G*n*[R]) and G*n*[R] dendrons ($n = 1$–4).

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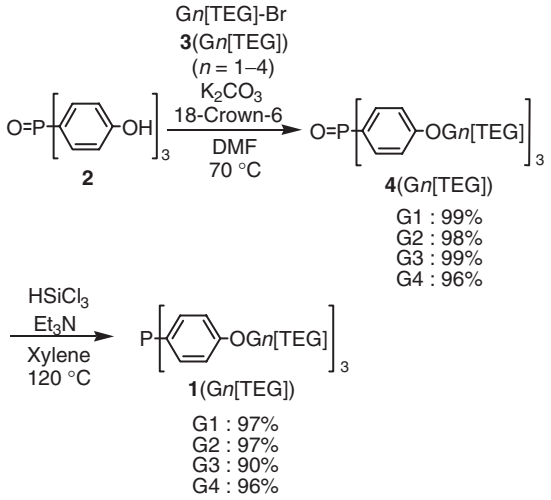
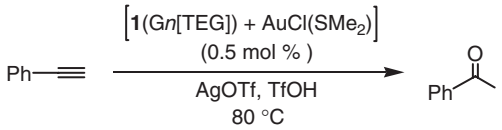


Scheme 1. Synthesis of dendrimer **1**(G*n*[TEG]).

Table 1. Hydration of Phenylacetylene Using **1**(G*n*[TEG])–Gold(I) Catalyst



Entry	G*n*	Solvent	AgOTf /mol %	TfOH /mol %	Time /h	Yield[a] /%
1	G1	H_2O	0	8	6	0
2	G1	H_2O	0.5	8	6	0
3	G1	MeOH–H_2O[b]	0	8	2	39
4	G1	MeOH–H_2O[b]	0.5	8	2	91
5	G1	MeOH–H_2O[b]	0.5	0	2	9
6	G2	MeOH–H_2O[b]	0.5	8	2	55
7	G3	MeOH–H_2O[b]	0.5	8	2	47

a) Determined by integration of ^{1}H NMR absorptions referred to an internal standard. b) MeOH:H_2O = 9:1 (v/v).

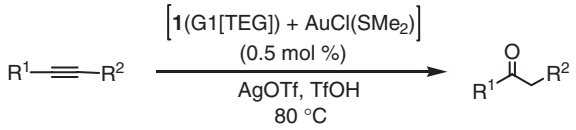
Results and Discussion

Novel phosphine core dendrimers having the tri(ethylene glycol) unit **1**(G*n*[TEG]) were synthesized according to Scheme 1. An *N*,*N*-dimethylformamide (DMF) solution of tris(4-hydroxyphenyl)phosphine oxide (**2**) and poly(benzyl ether) dendritic bromide **3**(G*n*[TEG]) was stirred at 70 °C in the presence of potassium carbonate and a catalytic amount of 18-crown-6 under an argon atmosphere. The obtained dendritic phosphine oxide **4**(G*n*[TEG]) was reduced by trichlorosilane in degassed xylene at 120 °C to afford dendritic phosphine **1**(G*n*[TEG]). Both transformations were carried out in fair yields in all generations.

By the use of **1**(G*n*[TEG]), we performed gold(I)-catalyzed hydration of phenylacetylene under acidic conditions. After the preparation of phosphine–gold(I) catalyst (0.5 mol %) by treatment of $AuCl(SMe_2)$ with **1**(G*n*[TEG]) and AgOTf (except for Entries 1 and 3), hydration of phenylacetylene was carried out at 80 °C in the presence of TfOH (except for Entry 5) (Table 1).

We first performed hydration of phenylacetylene through the use of the first-generation dendritic catalyst. Although dendritic phosphine–gold(I) catalyst **1**(G1[TEG])–AuCl was easily dissolved in water, hydration of phenylacetylene did not proceed in water, probably due to low solubility of phenylacetylene in water (Entry 1). In contrast, by carrying out the hydration in aqueous methanol (MeOH:H_2O = 9:1 (v/v)), the hydration of phenylacetylene proceeded to afford acetophenone in a 39% chemical yield (Entry 3). Furthermore, by the preparation of the corresponding gold(I) triflate **1**(G1[TEG])–AuOTf as a catalyst with the addition of AgOTf, the chemical yield of acetophenone was enhanced (91% for Entry 4) because of an increase of cationic property of the gold(I) catalyst.[4a] Even in the case of using gold(I) triflate as a catalyst, the absence of TfOH significantly decreased the chemical yield of acetophenone (9% for Entry 5).[10]

Table 2. Hydration of Various Alkynes Using **1**(G1[TEG])–Gold(I) Catalyst



Entry	R^1	R^2	Solvent	AgOTf /mol %	Time /h	Yield[a] /%
1	Ph	H	MeOH–H_2O[b]	0.5	2	91
2	Ph	Ph	MeOH–H_2O[b]	0.5	2	84
3	*n*-C_6H_{13}	H	MeOH–H_2O[b]	0.5	5	73
4	*n*-C_3H_7	*n*-C_3H_7	MeOH–H_2O[b]	0.5	5	54
5	CH_3	C_2H_4OH	H_2O	0	0.5	98
6	HOC_3H_6	H	H_2O	0	0.5	97
7	$HO_2CC_2H_4$	H	H_2O	0	0.5	98

a) Determined by integration of ^{1}H NMR absorptions referred to an internal standard. b) MeOH:H_2O = 9:1 (v/v).

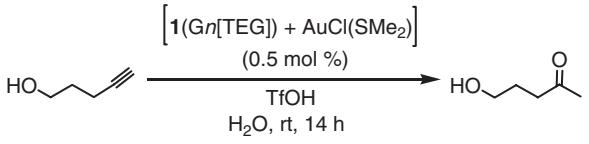
We subsequently performed this hydration using the second- and third-generation dendritic gold(I) catalysts. However the chemical yield of acetophenone was decreased by increasing the generation of the dendritic catalyst, probably due to steric hindrance of the dendron, contrary to our expectations (55% for Entry 6 and 47% for Entry 7).

Next, the hydrations of various alkynes were carried out through the use of the first-generation **1**(G1[TEG])–gold(I) catalyst (Table 2). In all cases, the hydration of alkynes proceeded smoothly to afford the corresponding ketones in fair yields. Especially in the case of alkynes having a hydroxy or carboxy group, the hydration reactions proceeded in water for 0.5 h in high chemical yields even without preparation of the corresponding gold(I) triflate, probably due to high solubility of these alkynes in water and the intramolecular nucleophilic coordination of –OH to a triple bond[11] (more than 97% for Entries 5–7).

Because water-soluble alkynes afforded high reactivity, we performed the hydration of 4-pentyn-1-ol through the use of various generation **1**(G*n*[TEG])–gold(I) catalysts at room temperature (Table 3). As a result, the first-generation dendritic gold(I) catalyst gave the highest chemical yield (93%), and the higher generation dendritic catalysts also afforded comparatively high chemical yields (G2: 89%, G3: 86%, and G4: 89%).

Since dendrimers with high generation are nano-order sized polymers, membrane separation by nanofiltration techniques is

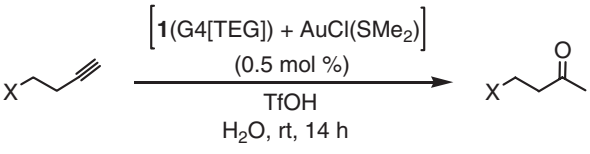
Table 3. Hydration Using Various Generation **1**(G*n*[TEG])–Gold(I) Catalysts



	G*n*			
	G1	G2	G3	G4
Yield[a)]/%	93	89	86	89

a) Determined by integration of ^{1}H NMR absorptions referred to an internal standard.

Table 4. Catalyst Recycling in Hydration



X	Yield[a)]/%			
	First	Second	Third	Fourth
CH_2OH	89	90	93	91
CO_2H	80	86	93	88

a) Determined by integration of ^{1}H NMR absorptions referred to an internal standard.

often used to recover the dendritic catalysts.[12] In this study, we examined the recycling of the dendritic catalyst in the hydration of 4-pentyn-1-ol and 4-pentynoic acid using 0.5 mol % of the fourth-generation **1**(G4[TEG])–gold(I) catalyst (Table 4). After the hydration had proceeded, the dendritic gold(I) catalyst was recovered by membrane separation by means of cross-flow mode nanofiltration of the aqueous reaction mixture.[13] The separated dendritic catalyst, which was not filtered, was subsequently reused. In both cases of 4-pentyn-1-ol and 4-pentynoic acid, **1**(G4[TEG])–gold(I) catalyst could be used four times without deactivation.[14] By membrane separation of the dendrimers based on their nano-order size, we could perform the recycling of the gold(I) catalyst in hydrations of alkynes without any organic solvent.

Conclusion

We have newly synthesized water-soluble phosphine core dendrimer having tri(ethylene glycol) units at the peripheral layer. By the use of this dendritic phosphine ligand, we prepared water-soluble dendritic phosphine–gold(I) catalyst, which caused the efficient hydration of alkynes. Furthermore, by membrane separation of the dendrimer based on nano-filtration of the reaction mixture, the dendritic phosphine–gold(I) catalyst was recovered and then subsequently reused. The immobilization of transition metal on water-soluble dendritic ligand appears to make possible the aqueous media catalyst-recyclable transformation.

Experimental

General. Kieselgel 60 F254 (Merck) was used for TLC, and Wakogel C-300 (Wako) was used for silica gel column chromatography. Reagents and dry solvents were commercially available and were used as received. The dendritic bromides **3**(G*n*[TEG]) ($n = 1$–3), which had been reported by McKeown et al.[15] were prepared by our previously reported synthetic procedures.[16] **3**(G4[TEG]) was newly synthesized from **3**(G3[TEG]) via the fourth-generation dendritic alcohol G4[TEG]–OH **5**. Tris(4-hydroxyphenyl)phosphine oxide (**2**) was prepared according to the literature method.[17]

Membrane separation was carried through the use of AS ONE pump tubing (7520-50) and PALL Minimate^{TM} (tangential flow filtration capsule) with a molecular weight cut-off (MWCO) of 650 Dalton.

IR spectra were recorded on a Thermo Electron Nicolet Nexus 470 FT-IR spectrophotometer. ^{1}H, ^{13}C, and ^{31}P NMR spectra were measured with a JEOL LA-500 spectrometer (^{1}H: 500 MHz, ^{13}C: 125 MHz, and ^{31}P: 202 MHz) or a JEOL JNM-LA400WB spectrometer (^{1}H: 400 MHz, ^{13}C: 100 MHz, and ^{31}P: 162 MHz). ^{1}H and ^{13}C NMR chemical shifts were recorded as ppm downfield from TMS as an internal standard. ^{31}P NMR data are given relative to external 85% H_3PO_4. Signal patterns are indicated as follows: brs, broad singlet; s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Coupling constants (J) are given in hertz (Hz). Mass spectra were measured with JEOL MS 600H (FAB; matrix: 3-nitrobenzyl alcohol) and Shimadzu AXIMA-CFR (MALDI-TOF; matrix: 2,5-dihydroxybenzoic acid) mass spectrometers. Microanalyses were performed with a CE Instruments EA1110 elemental analyzer.

Synthesis of the Fourth-Generation Dendritic Alcohol 5. A dry acetone solution (20 mL) of 3,5-dihydroxybenzyl alcohol (106 mg, 0.756 mmol), **3**(G3[TEG]) (3.416 g, 1.623 mmol), anhydrous potassium carbonate (281 mg, 2.03 mmol), and 18-crown-6 (36 mg, 0.136 mmol) was refluxed for 14 h under an argon atmosphere. The reaction mixture was filtered with Celite to remove inorganic salts, and the filtrate was evaporated to dryness. The residue was purified with silica gel column chromatography (ethyl acetate/methanol = 5/1 as eluent) to obtain the fourth-generation dendritic alcohol **5** (2.891 g, 0.6902 mmol) in a 91% yield.

3,5-Bis(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)benzyl Alcohol (5): Colorless oil; IR (Neat): 2875, 1596, 1449, 1373, 1350, 1322, 1297, 1247, 1173, 1145, 1068, 949, 843, 684 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.68–6.43 (m, 45H, ArH), 4.97 (brs, 12H, –CH_2Ar), 4.94 (brs, 16H, –CH_2Ar), 4.58 (d, $J = 12.0$ Hz, 2H, –CH_2Ar), 4.09 (t, $J = 4.7$ Hz, 32H, OC$H_2$$CH_2$O), 3.82 (t, $J = 4.7$ Hz, 32H, OCH_2-CH_2O), 3.73–3.62 (m, 96H, OC$H_2$$CH_2$O), 3.53 (t, $J = 4.7$ Hz, 32H, OC$H_2$$CH_2$O), 3.36 (s, 48H, OCH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.1, 144.0, 139.4, 139.2, 139.1, 106.5, 106.1, 101.6, 101.2, 71.9, 70.8, 70.6, 70.5, 70.1, 70.0, 69.7, 67.5, 59.0; Anal. Calcd for $C_{217}H_{316}O_{79}$: C, 62.22; H, 7.60%. Found: C, 61.85; H, 7.57%.

Synthesis of the Fourth-Generation Dendritic Bromide (3(G4[TEG])). To a dry THF solution (25 mL) of the fourth-generation dendritic alcohol **5** (2.598 g, 0.6202 mmol) and carbon tetrabromide (713 mg, 2.15 mmol) was added triphenylphosphine (567 mg, 2.16 mmol), and the reaction mixture was stirred at 40 °C for 2 h under an argon atmosphere. The reaction mixture was filtered with Celite, and the filtrate was evaporated to dryness. The residue was purified with silica gel column chromatography (ethyl acetate/methanol = 3/1 as eluent) to obtain the fourth-generation dendritic bromide **3**(G4[TEG]) (2.415 g, 0.5677 mmol) in a 92% yield.

3,5-Bis(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)benzyl Bromide (3(G4[TEG])): Colorless oil; IR (Neat): 2875, 1595, 1449, 1374, 1349, 1322, 1297, 1247, 1173, 1145, 1068, 949, 843, 684 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 6.69–6.44 (m, 45H, ArH), 4.97 (brs, 12H, $-CH_2Ar$), 4.95 (brs, 16H, $-CH_2Ar$), 4.40 (s, 2H, $-CH_2Ar$), 4.10 (t, $J = 4.8$ Hz, 32H, OCH_2CH_2O), 3.83 (t, $J = 4.7$ Hz, 32H, OCH_2CH_2O), 3.72–3.63 (m, 96H, OCH_2CH_2O), 3.53 (t, $J = 4.6$ Hz, 32H, OCH_2CH_2O), 3.36 (s, 48H, OCH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.0, 139.8, 139.0, 138.9, 106.4, 101.5, 101.0, 71.9, 70.7, 70.6, 70.5, 70.0, 69.9, 69.6, 67.4, 59.0; Anal. Calcd for $C_{217}H_{315}O_{78}Br$: C, 61.31; H, 7.47; Br, 1.88%. Found: C, 60.99; H, 7.36; Br, 1.59%.

Synthesis of Dendritic Phosphine Oxide 4(G*n*[TEG]) from 2 and 3(G*n*[TEG]): Typical Procedure. A dry DMF solution (10 mL) of tris(4-hydroxyphenyl)phosphine oxide (**2**) (23 mg, 0.070 mmol), the fourth-generation dendritic bromide **3**(G4[TEG]) (0.988 g, 0.232 mmol), anhydrous potassium carbonate (49 mg, 0.36 mmol), and 18-crown-6 (20 mg, 0.076 mmol) was stirred at 70 °C for 4 h under an argon atmosphere. The reaction mixture was filtered with Celite to remove inorganic salts, and the filtrate was evaporated to dryness. The residue was purified with silica gel column chromatography (ethyl acetate/methanol = 3/1 as eluent) to obtain **4**(G4[TEG]) (0.860 g, 0.0670 mmol) in a 96% yield.

Tris{4-[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]phenyl}-phosphine Oxide (4(G1[TEG])): Colorless oil; IR (CH_2Cl_2) 2876, 1596, 1501, 1450, 1294, 1249, 1176, 1119, 834, 672, 543 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.56 (dd, $J = 11.5$, 8.0 Hz, 6H, ArH), 7.00 (d, $J = 8.0$ Hz, 6H, ArH), 6.58 (s, 6H, ArH), 6.45 (s, 3H, ArH), 5.01 (s, 6H, OCH_2Ar), 4.11 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.85 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.74 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.68 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.66 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.55 (t, $J = 4.5$ Hz, 12H, OCH_2CH_2O), 3.37 (s, 18H, OCH_3); ^{13}C NMR (125 MHz, $CDCl_3$): δ 161.3 ($^4J_{C-P} = 3$ Hz), 160.1, 138.5, 133.8 ($^2J_{C-P} = 11$ Hz), 124.7 ($^1J_{C-P} = 110$ Hz), 114.7 ($^3J_{C-P} = 13$ Hz), 106.0, 101.0, 71.8, 70.7, 70.55, 70.46, 69.8, 69.5, 67.4, 58.9; ^{31}P NMR (202 MHz, $CDCl_3$): δ 28.5; FABMS for $C_{81}H_{117}O_{28}P$ m/z: Calcd: 1569.8 $[M]^+$; Found: 1569; Anal. Calcd for $C_{81}H_{117}O_{28}P$: C, 61.97; H, 7.51%. Found: C, 61.64; H, 7.44%.

Tris(4-{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]-benzyloxy}phenyl)phosphine Oxide (4(G2[TEG])): Colorless oil; IR (CH_2Cl_2) 2875, 1596, 1473, 1458, 1449, 1375, 1350, 1296, 1248, 1175, 1119, 1070, 844 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.59 (dd, $J = 11.5$, 8.8 Hz, 6H, ArH), 7.03 (dd, $J = 8.8$, 2.0 Hz, 6H, ArH), 6.65 (d, $J = 2.0$ Hz, 6H, ArH), 6.59 (d, $J = 2.0$ Hz, 12H, ArH), 6.55 (t, $J = 2.0$ Hz, 3H, ArH), 6.44 (t, $J = 2.0$ Hz, 6H, ArH), 5.01 (s, 6H, OCH_2Ar), 4.95 (s, 12H, OCH_2Ar), 4.11 (t, $J = 4.5$ Hz, 24H, OCH_2CH_2O), 3.84 (t, $J = 4.5$ Hz, 24H, OCH_2CH_2O), 3.74–3.70 (m, 24H, OCH_2CH_2O), 3.69–3.63 (m, 48H, OCH_2CH_2O), 3.54 (dd, $J = 6.5$, 4.3 Hz, 24H, OCH_2CH_2O), 3.36 (s, 36H, OCH_3); ^{13}C NMR (125 MHz, $CDCl_3$): δ 161.5, 160.13, 160.10, 139.0, 138.6, 134.0 ($^2J_{C-P} = 11$ Hz), 124.8 ($^1J_{C-P} = 109$ Hz), 114.8 ($^3J_{C-P} = 14$ Hz), 106.4, 106.1, 101.6, 101.1, 71.9, 70.8, 70.63, 70.55, 70.02, 69.97, 69.7, 67.5, 59.0; ^{31}P NMR (202 MHz, $CDCl_3$): δ 28.6; MALDI-TOFMS for $C_{165}H_{237}O_{58}P$ m/z: Calcd: 3180.5 $[M + H]^+$; Found: 3180.5; Anal. Calcd for $C_{165}H_{237}O_{58}P$: C, 62.32; H, 7.53%. Found: C, 62.15; H, 7.52%.

Tris[4-(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)phenyl]phosphine Oxide (4(G3-[TEG])): Colorless oil; IR (CH_2Cl_2) 2876, 1596, 1449, 1374, 1350, 1323, 1297, 1174, 1144, 1120, 1069 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 7.61 (dd, $J = 11.5$, 8.0 Hz, 6H, ArH), 7.06 (dd, $J = 9.0$, 1.5 Hz, 6H, ArH), 6.71 (d, $J = 2.0$ Hz, 6H, ArH), 6.67 (d, $J = 2.5$ Hz, 12H, ArH), 6.60 (t, $J = 2.5$ Hz, 3H, ArH), 6.58 (d, $J = 2.0$ Hz, 24H, ArH), 6.54 (t, $J = 2.5$ Hz, 6H, ArH), 6.44 (t, $J = 2.5$ Hz, 12H, ArH), 5.02 (s, 6H, OCH_2Ar), 4.97 (s, 12H, OCH_2Ar), 4.95 (s, 24H, OCH_2Ar), 4.10 (t, $J = 4.5$ Hz, 48H, OCH_2CH_2O), 3.83 (t, $J = 4.5$ Hz, 48H, OCH_2CH_2O), 3.74–3.69 (m, 48H, OCH_2CH_2O), 3.68–3.62 (m, 96H, OCH_2CH_2O), 3.53 (dd, $J = 5.5$, 3.0 Hz, 48H, OCH_2CH_2O), 3.36 (s, 72H, OCH_3); ^{13}C NMR (125 MHz, $CDCl_3$): δ 161.4, 160.1, 160.0, 138.9, 138.5, 133.8 ($^2J_{C-P} = 10$ Hz), 114.3 ($^3J_{C-P} = 13$ Hz), 106.5, 106.0, 101.5, 101.4, 101.0, 71.8, 70.7, 70.55, 70.46, 70.0, 69.9, 69.6, 67.4, 58.9; ^{31}P NMR (202 MHz, $CDCl_3$): δ 28.4; Anal. Calcd for $C_{333}H_{477}O_{118}P$: C, 62.49; H, 7.53%. Found: C, 62.72; H, 7.53%.

Tris{4-[3,5-bis(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)benzyloxy]phenyl}phosphine Oxide (4(G4[TEG])): Colorless oil; IR (Neat): 2875, 1596, 1449, 1373, 1349, 1323, 1297, 1248, 1173, 1149, 1069, 949, 844, 684 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.64 (t, $J = 12.0$ Hz, 6H, ArH), 7.09 (d, $J = 7.0$ Hz, 6H, ArH), 6.75–6.42 (m, 135H, ArH), 5.02 (brs, 6H, $-CH_2Ar$), 4.98 (brs, 12H, $-CH_2Ar$), 4.96 (brs, 24H, $-CH_2Ar$), 4.92 (brs, 48H, $-CH_2Ar$), 4.08 (t, $J = 4.2$ Hz, 96H, OCH_2CH_2O), 3.81 (t, $J = 5.0$ Hz, 96H, OCH_2CH_2O), 3.71–3.61 (m, 288H, OCH_2CH_2O), 3.51 (t, $J = 4.7$ Hz, 96H, OCH_2CH_2O), 3.34 (s, 144H, OCH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.14, 160.08, 139.1, 139.0, 133.9 ($^2J_{C-P} = 11$ Hz), 114.8 ($^3J_{C-P} = 13$ Hz), 106.7, 106.5, 106.1, 101.5, 101.1, 71.9, 70.8, 70.6, 70.5, 67.0, 69.6, 67.5, 59.0; ^{31}P NMR (162 MHz, $CDCl_3$): δ 28.9; Anal. Calcd for $C_{669}H_{957}O_{238}P$: C, 62.59; H, 7.51%. Found: C, 62.49; H, 7.44%.

Synthesis of Dendritic Phosphine 1(G*n*[TEG]) from 4(G*n*-[TEG]): Typical Procedure. To a solution of **4**(G2[TEG]) (1.827 g, 0.575 mmol) in degassed xylene (11 mL) was added triethylamine (288.4 mg, 2.85 mmol) and trichlorosilane (309 mg, 2.28 mmol) at room temperature with stirring. The mixture was stirred at 120 °C for 16 h under an argon atmosphere. To a reaction mixture was added dichloromethane (20 mL), water (1 mL), and sodium hydrogen carbonate (ca. 0.7 g), and the thus obtained mixture was stirred at room temperature for 2 h. After the removal of water by the addition of magnesium sulfate (ca. 2 g), the mixture was filtered with Celite to remove inorganic salts, and the filtrate was evaporated to dryness. The residue was purified with silica gel column chromatography (dichloromethane/methanol = 10/1 as eluent) to obtain **1**(G2[TEG]) (1.751 g, 0.553 mmol) in a 97% yield.

Tris{4-[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]phenyl}-phosphine (1(G1[TEG])): Yellow oil; IR (CH_2Cl_2) 2875, 1594, 1496, 1449, 1350, 1293, 1176, 1109, 1072, 829, 530 cm^{-1}; ^1H NMR (500 MHz, C_6D_6): δ 7.42 (dd, $J = 9.0$, 7.5 Hz, 6H, ArH), 6.89 (d, $J = 7.5$ Hz, 6H, ArH), 6.65 (d, $J = 2.0$ Hz, 6H, ArH), 6.54 (t, $J = 2.0$ Hz, 3H, ArH), 4.69 (s, 6H, OCH_2Ar), 3.78 (t, $J = 5.0$ Hz, 12H, OCH_2CH_2O), 3.53 (t, $J = 5.0$ Hz, 12H, OCH_2CH_2O), 3.48–3.44 (m, 36H, OCH_2CH_2O), 3.34 (dd, $J = 5.5$, 4.0 Hz, 12H, OCH_2CH_2O), 3.12 (s, 18H, OCH_3); ^{13}C NMR (125 MHz, C_6D_6): δ 160.9, 159.9, 139.8, 135.6 ($^2J_{C-P} = 21$ Hz), 130.2 ($^1J_{C-P} = 9$ Hz), 115.6 ($^3J_{C-P} = 7$ Hz), 106.4, 101.5, 72.4, 71.14, 71.05, 70.9, 70.1, 69.9, 67.7, 58.7; ^{31}P NMR (202 MHz, C_6D_6): δ −9.7; FABMS for $C_{81}H_{117}O_{27}P$ m/z: Calcd: 1553.8 $[M]^+$; Found: 1553.8; Anal. Calcd for $C_{81}H_{117}O_{27}P$: C, 62.61; H, 7.59%. Found: C, 62.61; H, 7.50%.

Tris(4-{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]-

benzyloxy}phenyl)phosphine (1(G2[TEG])): Colorless oil; IR (CH_2Cl_2) 2875, 1595, 1496, 1449, 1374, 1350, 1323, 1296, 1243, 1175, 1144, 1069, 949, 845 cm^{-1}; ^1H NMR (500 MHz, C_6D_6): δ 7.44 (t, $J = 8.0$ Hz, 6H, ArH), 6.93 (d, $J = 8.0$ Hz, 6H, ArH), 6.77 (d, $J = 2.5$ Hz, 6H, ArH), 6.74 (t, $J = 2.5$ Hz, 3H, ArH), 6.69 (d, $J = 2.5$ Hz, 12H, ArH), 6.56 (t, $J = 2.5$ Hz, 6H, ArH), 4.77 (s, 12H, OCH_2Ar), 4.74 (s, 6H, OCH_2Ar), 3.83 (t, $J = 5.0$ Hz, 24H, OCH_2CH_2O), 3.56 (t, $J = 5.0$ Hz, 24H, OCH_2CH_2O), 3.50–3.45 (m, 72H, OCH_2CH_2O), 3.35 (dd, $J = 5.5$, 4.0 Hz, 24H, OCH_2-CH_2O), 3.13 (s, 36H, OCH_3); ^{13}C NMR (125 MHz, C_6D_6): δ 160.85, 160.78, 159.9, 140.0, 139.9, 135.6 ($^2J_{C-P} = 21$ Hz), 128.5, 115.6 ($^3J_{C-P} = 7$ Hz), 106.9, 106.4, 102.2, 101.5, 72.4, 71.1, 71.0, 70.9, 70.2, 70.1, 69.9, 67.8, 53.4; ^{31}P NMR (202 MHz, C_6D_6): δ −9.6; MALDI-TOFMS for $C_{165}H_{237}O_{57}P$ *m/z*: Calcd: 3163.55 $[M + H]^+$; Found: 3163.29; Anal. Calcd for $C_{165}H_{237}O_{57}P$: C, 62.64; H, 7.57%. Found: C, 62.88; H, 7.58%.

Tris[4-(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)phenyl]phosphine (1(G3[TEG])): Yellow oil; IR (CH_2Cl_2) 2875, 1595, 1496, 1449, 1373, 1350, 1323, 1297, 1244, 1175, 1145, 1069, 950, 845, 684 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.26 (t, $J = 8.1$ Hz, 6H, ArH), 6.97 (d, $J = 8.1$ Hz, 6H, ArH), 6.70 (d, $J = 2.1$ Hz, 6H, ArH), 6.67 (d, $J = 2.1$ Hz, 12H, ArH), 6.58 (d, $J = 2.3$ Hz, 27H, ArH), 6.54 (brs, 6H, ArH), 6.44 (t, $J = 2.2$ Hz, 12H, ArH), 4.96 (brs, 42H, $-CH_2Ar$), 4.10 (t, $J = 4.8$ Hz, 48H, OCH_2CH_2O), 3.82 (t, $J = 4.9$ Hz, 48H, OCH_2CH_2O), 3.74–3.62 (m, 144H, OCH_2CH_2O), 3.53 (dd, $J = 5.5$, 3.0 Hz, 48H, OCH_2CH_2O), 3.35 (s, 72H, OCH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.1, 160.0, 159.2, 139.04, 139.00, 138.6, 134.9 ($^2J_{C-P} = 20$ Hz), 114.9 ($^3J_{C-P} = 7.4$ Hz), 101.5, 101.1, 71.8, 70.7, 70.5, 70.4, 69.9, 69.6, 67.4, 60.3, 58.9; ^{31}P NMR (162 MHz, $CDCl_3$): δ −8.8; Anal. Calcd for $C_{333}H_{477}O_{117}P$: C, 62.66; H, 7.53%. Found: C, 62.76; H, 7.54%.

Tris{4-[3,5-bis(3,5-bis{3,5-bis[3,5-di(1,4,7,10-tetraoxaundecyl)benzyloxy]benzyloxy}benzyloxy)benzyloxy]phenyl}phosphine (1(G4[TEG])): Colorless oil; IR (Neat): 2876, 1595, 1449, 1373, 1349, 1323, 1297, 1245, 1174, 1145, 1069, 949, 843, 684 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 6.9 (d, $J = 8.8$ Hz, 6H, ArH), 6.74–6.42 (m, 141H, ArH), 4.95 (brs, 42H, $-CH_2Ar$), 4.92 (brs, 48H, $-CH_2Ar$), 4.07 (t, $J = 4.7$ Hz, 96H, OCH_2CH_2O), 3.80 (t, $J = 4.7$ Hz, 96H, OCH_2CH_2O), 3.70–3.60 (m, 288H, OCH_2CH_2O), 3.51 (t, $J = 4.7$ Hz, 96H, OCH_2CH_2O), 3.34 (s, 144H, OCH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 160.2, 160.1, 160.0, 139.1, 139.0, 135.0 ($^2J_{C-P} = 21$ Hz), 114.9 ($^3J_{C-P} = 7.2$ Hz), 106.5, 106.0, 101.5, 101.1, 71.8, 70.7, 70.5, 70.4, 69.9, 69.6, 67.4, 60.3, 58.9; ^{31}P NMR (162 MHz, $CDCl_3$): δ −8.3; Anal. Calcd for $C_{669}H_{957}O_{237}P$: C, 62.66; H, 7.52%. Found: C, 62.59; H, 7.21%.

Hydration of Alkynes: General Procedure. The dendritic phosphine–gold(I) complex was prepared by treatment of $AuCl(SMe_2)$ (0.015 mmol) with **1**(G*n*[TEG]) (0.015 mmol) at room temperature in aqueous methanol (3 mL; MeOH:H_2O = 9:1 (v/v)) under an argon atmosphere. After stirring for 0.5 h, AgOTf was subsequently added, and the mixture was stirred for 0.5 h at room temperature. To the resulting solution of the dendritic gold(I) complex **1**(G*n*[TEG])–AuOTf was added an alkyne (3.0 mmol) and CF_3SO_3H (0.24 mmol), and the reaction mixture was stirred at 80 °C for 2–5 h. After the addition of saturated aqueous solution of sodium hydrogen carbonate, the mixture was extracted with diethyl ether (15 mL × 3). The organic layer was washed with brine and was dried over magnesium sulfate. After removal of the organic solvent under reduced pressure, the chemical yield of the hydration product was determined by the integration of ^1H NMR absorption referred to an internal standard.

Catalyst Recycling Experiment. The dendritic phosphine–gold(I) complex was prepared by treatment of $AuCl(SMe_2)$ (0.015 mmol) with the fourth-generation dendritic phosphine **1**(G4[TEG]) (0.015 mmol) at room temperature in water (3 mL) under an argon atmosphere, and the mixture was stirred for 0.5 h. To the resulting solution of the dendritic gold(I) complex **1**(G4[TEG])–AuCl was added an alkyne (3.0 mmol) and CF_3SO_3H (0.24 mmol), and the reaction mixture was stirred at room temperature for 14 h. Under membrane separation system,[13] the aqueous reaction mixture, which was diluted with water (40 mL), was concentrated to 2–3 mL by cross-flow mode nanofiltration by pumping the reaction mixture (repeated 4 times). The concentrated reaction mixture, which contained the dendritic phosphine–gold(I) catalyst, was reused for another hydration by employing an alkyne (3.0 mmol) and CF_3SO_3H (0.24 mmol).

The filtered solution was concentrated under reduced pressure, and the chemical yield of the hydration product was determined by the integration of ^1H NMR absorption referred to an internal standard.

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Supporting Information

Figure showing membrane separation. This material is available free of charge on the Web at: http://www.csj.jp/journals/bcsj/.

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