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Dendritic poly(ether–imide)s: synthesis, characterization, and modification

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Abstract

A convergent approach to the preparation of dendritic macromolecules with an aromatic ether–imide inner structure and modifiable benzyl ether chain ends is described. The structural component that constitutes the branching regions was derived from 1-(4-aminophenyl)-1,1-bis(4-hydroxyphenyl)ethane. The key steps in ether–imide dendron synthesis involve an aromatic nucleophilic displacement of an activated nitro group with phenoxide leading to the ether linkage and cyclocondensation of the amino group with 3-nitrophthalic anhydride, to give rise to the imide ring containing an activated nitro functionality. The dendritic wedges are then coupled to a polyfunctional core to complete the synthesis. The benzyl ether chain ends can be selectively removed by catalytic hydrogenolysis to produce a dendrimer with phenolic chain ends. Further modification of the chain ends is accomplished by etherfication of the phenolic groups. Structures of these dendritic poly(ether–imide)s were confirmed by ^{1}H NMR, ^{13}C NMR and FTIR spectroscopy as well as by mass spectrometry. Properties such as the glass transition temperature and solubility of the dendrimer are greatly affected by the nature of the end groups.

Keywords: Dendritic poly(ether–imide)s; Glass transition temperature; Solubility

1. Introduction

Dendritic macromolecules are characterized by a central polyfunctional core, from which monomeric units with branching points arise successively. This results in a nearly entanglement-free, highly branched spherical structure, the periphery of which consists of a large number of chain ends. Because such compounds have unique highly branched polymeric structures and well defined 3D architectures, it would appear that they have great potential for chemical applications. As a result of this, dendritic macromolecules have received considerable attention in recent years [1–45].

Two different synthetic strategies are currently adopted for synthesizing dendritic macromolecules, namely the divergent [46,47] and convergent growth approaches [48–50]. In the divergent approach [46,47], synthesis starts from the center of the dendrimer and proceeds "outwards", via the coupling of building blocks. This approach provides for regular branching around a core molecule. In the convergent approach [48–50], construction begins at what will eventually become the periphery of the final macromolecules and proceeds "inwards", followed by the attachment of dendritic wedges to a polyfunctional core. Since the synthesis of dendritic macromolecules is based on the interactive strategy, control of the architectural properties is maintained at each synthetic step. The synthesis of well defined, highly branched macromolecules with tunable interior/surface features and a controlled molecular size has sparked considerable interest, in anticipation of generating functional materials with desirable properties.

One of the intriguing prospects of the dendritic architecture is the large number of chain-end functional groups that can be tailor-made to yield dendritic molecules with unique chemical and physical properties. In this paper, we report the synthesis and characterization of ether–imide dendrimers with modifiable benzyl ether groups located at the peripheries. The preparation of dendritic poly(ether–imide)s utilized the convergent strategy, involving the synthesis of dendritic wedges, which contained ether–imides as the structural components and benzyl ether as the chain-end groups, followed by their attachment to the core component. Structural components that constitute the branching regions of the dendritic wedges were derived

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from 1-(4-aminophenyl)-1,1-bis(4-hydroxyphenyl)ethane (2) and 3-nitrophthalic anhydride, while the core was derived from 1,1,1-tris(4-hydroxyphenyl)ethane. To modify the chain ends of the dendritic macromolecules, a protection–deprotection approach was employed. The benzyl group at the chain ends can be selectively removed by hydrogenolysis [51,52], thus generating the phenolic-terminated poly(ether–imide)s. Reaction of the peripheral phenolic groups with *n*-hexanol via the Mitsunobu reaction [53] led to dendrimers with *n*-hexyl ether chain ends. Such transformations of the terminal functionalities were shown to dramatically alter the thermal and solution behavior of the various surface modified dendrimers.

2. Experimental section

2.1. General directions

The CH_3ONa/CH_3OH solution was prepared by dissolving sodium metal in absolute MeOH. THF was distilled from a sodium diphenyl ketyl solution just prior to use. Other starting materials and reagents were used as obtained from commercial suppliers. Nuclear magnetic resonance (NMR) spectra were recorded on a Varian Unity 300 MHz or a Bruker-DRX 300 MHz spectrometer. Infrared spectra were obtained on a Nicolet 520 FTIR Spectrometer. Mass spectra were obtained on a JEOL JMS-SX/SX 102A Mass Spectrometer. Differential scanning calorimetry (DSC) was performed on a SEIKO SSC 5200 DSC using a heating/cooling rate of 10°C min^{-1}. Samples were scanned from 30 to 300°C and then cooled to 30°C and scanned a second time from 30 to 300°C. Glass transition temperatures were determined from the second heating scan. Size-exclusion chromatography (SEC) was carried out on a Waters chromatography interfaced with a Waters 410 Differential refractometer. Three 5-μm Waters styragel columns (300 × 7.8 mm) connected in series in decreasing order of pore size (10^5, 10^4, and 10^3 Å) were used with DMF/0.05 M LiBr, as eluant, and poly(methyl methacrylate) standard samples were used for the calibration. Matrix-assisted laser desorption/ionization (MALDI) mass spectra were recorded on a linear time-of-flight mass spectrometer (TOF-MS) (HP G2025A) equipped with a pulsed nitrogen laser (337 nm). Minimum laser power was used to desorb the analyte from the sample solution. An aliquot of 1 μL of the sample (1 mM) was briefly vortexed with 10 μl of matrix (100 mM), followed by the addition of 1 μL of saturated ethanolic solution of KCl or $AgNO_3$. One microliter of the resulting solution was transferred to the sample probe and dried under reduced pressure. The measurement was performed in positive ion mode using either 2,5-dihydroxybenzoic acid or retinoic acid, as the matrix. The observed molecular masses were calibrated against bovine insulin and bradykinin standards, and the instrument gave *m*/*z* values within 0.5% resolution. Analytical TLC was performed on commercial Merck plates coated with silica gel GF254. Silica gel for column chromatography was Merck Kieselgel 60 (70–230 mesh). The synthesis of compounds **1** and **2** has been reported elsewhere [54].

1,1-Bis(4-benzyloxy)phenyl-1-(4-nitrophenyl)ethane (3). A mixture of **1** (10.0 g, 29.8 mmol), benzyl bromide (10.2 g, 59.6 mmol), K_2CO_3 (12.4 g, 89.6 mmol), and 18-crown-6 (1.5 g) in anhydrous acetone (100 ml) was heated at reflux with vigorous stirring under nitrogen for 5 h. The resulting mixture was poured into water (300 ml) and extracted with EtOAc (3 × 150 ml). The combined extracts were dried over $MgSO_4$ and the solvent removed in vacuo to give **3** (14.9 g, 97.0%). ^{1}H NMR ($CDCl_3$) δ 2.07 (s, 3H), 4.96 (s, 4H), 6.81 (d, 4H, $J = 8.8$ Hz), 6.89 (d, 4H, $J = 8.8$ Hz), 7.18 (d, 2H, $J = 8.2$ Hz), 7.23–7.30 (m, 10H), 8.01 (d, 2H, $J = 8.2$ Hz). ^{13}C NMR ($CDCl_3$) δ 30.5, 51.6, 70.0, 114.3, 123.0, 127.5, 128.0, 128.6, 129.5, 136.9, 140.1, 146.2, 157.2, 157.4. MS (*m*/*z*): obs. 515.2090; calcd. 515.2096 for $C_{34}H_{29}O_4N$.

[G1]-NH_2. To a mixture of **3** (14.9 g, 28.9 mmol) and iron powder (8.0 g) in ethanol (300 ml), 12 N HCl (15.0 ml) was added dropwise, followed by heating at reflux for 5 h. The reaction mixture was poured into water (300 ml) and extracted with EtOAc (3 × 200 ml). The combined extracts were dried over $MgSO_4$ and the solvent was removed in vacuo to give **[G-1]-NH_2** (13.9 g, 99.1%). ^{1}H NMR ($CDCl_3$) δ 2.08 (s, 3H), 5.02 (s, 4H), 6.60 (d, 2H, $J = 8.7$ Hz), 6.85 (d, 4H, $J = 9.0$ Hz), 6.86 (d, 2H, $J = 9.0$ Hz), 7.00 (d, 4H, $J = 9.3$ Hz), 7.28–7.43 (m, 10H). ^{13}C NMR ($CDCl_3$) δ 30.7, 50.5, 69.9, 113.8, 114.5, 127.5, 127.9, 128.5, 129.4, 129.6, 137.1, 139.7, 142.2, 144.0, 156.7. MS (*m*/*z*): obs. 485.2357; calcd. 485.2355 for $C_{34}H_{31}O_2N$.

[G1]-NO_2. A mixture of **[G1]-NH_2** (13.9 g, 28.6 mmol) and 3-nitrophthalic anhydride (5.5 g, 28.5 mol) in AcOH (200 ml) was refluxed under nitrogen for 6 h. The mixture was cooled to 25°C and added to water (600 ml). The resulting precipitate was filtrated and purified by column chromatography ($EtOAc/CH_2Cl_2$ 1:40) to give **[G1]-NO_2** (13.1 g, 69.6%). ^{1}H NMR ($CDCl_3$) δ 2.16 (s, 3H), 5.05 (s, 4H), 6.89 (d, 4H, $J = 8.7$ Hz), 7.03 (d, 4H, $J = 8.7$ Hz), 7.20–7.50 (m, 14H), 7.97 (dd, 1H, $J = 7.2$,8.1 Hz), 8.15 (d, 1H, $J = 8.1$ Hz), 8.21 (d, 1H, $J = 7.2$ Hz). ^{13}C NMR ($CDCl_3$) δ 30.6, 51.2, 69.9, 114.0, 123.2, 125.6, 127.3, 127.5, 127.9, 128.5, 128.7, 129.4, 129.6, 133.6, 135.6, 136.9, 141.0, 145.2, 150.2, 156.9, 161.9, 164.8. MS (*m*/*z*): obs. 660.2260; calcd. 660.2260 for $C_{42}H_{32}O_6N_2$.

[G2]-NH_2. A mixture of **2** (2.0 g, 6.6 mmol) and CH_3ONa (26.0 ml, 13.3 mmol, 0.51 M in CH_3OH) was stirred under nitrogen at 25°C for 1 h, and the CH_3OH was then removed in vacuo. The solid was further dried at 60°C in vacuo for 2 h. To the resulting solid was added anhydrous DMF and **[G1]-NO_2** (8.7 g, 13.2 mmol). The mixture was stirred at 60°C for 12 h, and then added to water. The precipitate was isolated by filtration and purified by column

chromatography (EtOAc/CH_2Cl_2 1:50) to give **[G2]-NH_2** (6.2 g, 61.3%). ^{1}H NMR ($CDCl_3$) δ 2.16 (br, 9H), 5.03 (s, 8H), 6.66 (d, 2H, $J = 7.8$ Hz), 6.89 (m, 10H), 7.03 (m, 12H), 7.11–7.24 (m, 10H), 7.28–7.44 (m, 24H), 7.62 (m, 4H). ^{13}C NMR ($CDCl_3$) δ 30.7, 51.2, 69.9, 114.0, 114.8, 117.8, 118.8, 119.4, 123.1, 125.7, 127.5, 127.9, 128.5, 129.2, 129.4, 129.7, 130.3, 133.9, 134.0, 136.0, 137.0, 138.6, 141.2, 144.2, 146.2, 149.3, 153.0, 155.0, 156.9, 165.1, 166.8. MS (*m/z*): obs. 1531.5934; calcd.1531.5921 for $C_{104}H_{81}O_{10}N_3$.

[G2]-NO_2. This was prepared from **[G2]-NH_2** (7.99 g, 5.22 mmol) and 3-nitrophthalic anhydride (1.05 g, 5.44 mmol) using the same procedure described for **[G1]-NO_2**. The crude product was purified by column chromatography (EtOAc/CH_2Cl_2 1:50) to give **[G2]-NO_2** (5.3 g, 59.5%). ^{1}H NMR ($CDCl_3$) δ 2.18 (s, 6H), 2.23 (s, 3H), 5.02 (s, 8H), 6.86 (d, 8H, $J = 8.1$ Hz), 7.02 (d, 8H, $J = 8.7$ Hz), 7.06 (d, 4H, $J = 7.8$ Hz), 7.11–7.24 (m, 12H), 7.25–7.50 (m, 26H), 7.63–7.68 (m, 4H), 7.96 (dd, 1H, $J = 7.8$,8.1 Hz), 8.14 (d, 1H, $J = 8.1$ Hz), 8.20 (d, 1H, $J = 7.8$ Hz). ^{13}C NMR ($CDCl_3$) δ 30.7, 51.2, 51.8, 69.9, 114.0, 118.0, 119.0, 119.5, 123.3, 125.7, 125.9, 127.5, 127.9, 128.5, 128.9, 129.0, 129.2, 129.4, 129.7, 130.3, 133.6, 134.0, 135.8, 136.1, 137.0, 141.3, 145.0, 145.4, 149.1, 149.4, 153.4, 154.8, 156.9, 161.9, 164.8, 165.1, 166.7. MS (*m/z*): obs. 1707.5883; calcd.1707.5905 for $C_{112}H_{83}O_{14}N_4$.

[G1]$_3$[C]. A mixture of 1,1,1-tris(4-hydroxyphenyl)-ethane (250 mg, 817 μmol) and CH_3ONa (4.9 ml, 2.5 mmol, 0.50 M in CH_3OH) was stirred under nitrogen at 25°C for 1 h. The CH_3OH was removed in vacuo, and the resulting solid was dried at 60°C in vacuo for 2 h. To this solid, anhydrous DMF (8 ml) and **[G1]-NO_2** (1.68 g, 2.55 mmol) were added. The mixture was stirred at 60°C for 12 h, and then poured into water. The precipitated solid was isolated by filtration and purified by column chromatography (EtOAc/$CHCl_3$ 1:60) to give **[G1]$_3$[C]** (753 mg, 42.9%). ^{1}H NMR ($CDCl_3$) δ 2.13 (s, 9H), 2.21 (s, 3H), 5.02 (s, 12H), 6.86 (d, 12H, $J = 9.3$ Hz), 7.01 (d, 12H, $J = 8.7$ Hz), 7.05 (d, 6H, $J = 9.0$ Hz), 7.15 (m, 9H), 7.18 (d, 6H, $J = 8.4$ Hz), 7.30–7.43 (m, 36H), 7.64 (m, 6H). ^{13}C NMR ($CDCl_3$) δ 30.7, 51.2, 51.5, 70.0, 114.1, 118.0, 119.0, 119.5, 123.4, 125.7, 127.5, 127.9, 128.5, 129.3, 129.7, 130.2, 134.0, 136.1, 137.0, 141.2, 145.3, 149.4, 153.4, 154.8, 156.9, 165.1, 166.7.

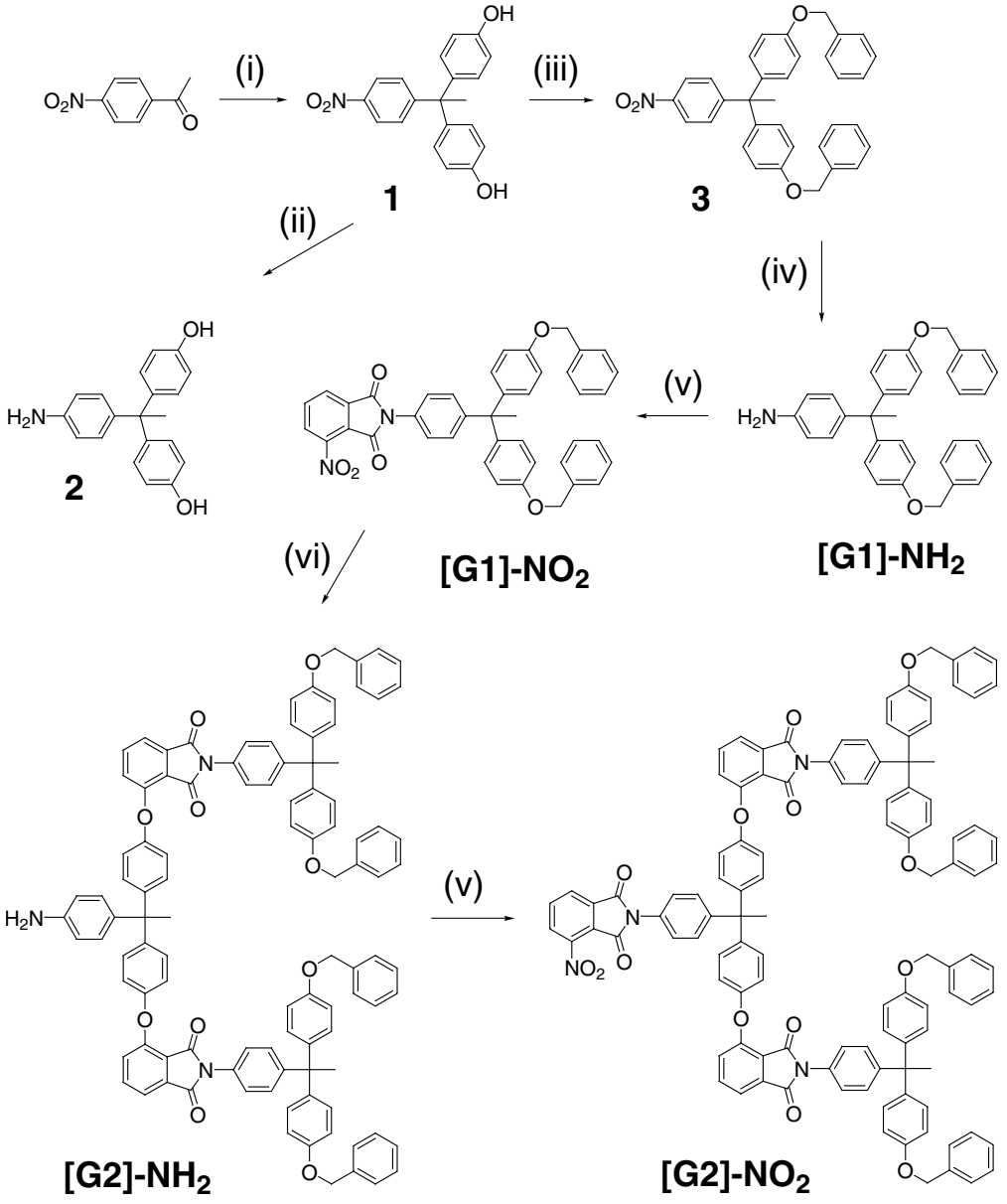
[G2]$_3$[C]. This was prepared from 1,1,1-tris(4-hydroxyphenyl)ethane (100 mg, 327 μmol), CH_3ONa (2.0 ml, 1.0 mmol, 0.50 M in CH_3OH), and **[G2]-NO_2** (1.80 g, 1.06 mmol) using the procedure described for **[G1]$_3$[C]**. The product was purified by column chromatography (EtOAc/$CHCl_3$ = 1:50) to give **[G2]$_3$[C]** (530 mg, 30.7%). ^{1}H NMR ($CDCl_3$) δ 2.13 (s, 18H), 2.22 (s, 12H), 5.01 (s, 24H), 6.86 (d, 24H, $J = 8.9$ Hz), 7.02 (d, 24H, $J = 8.9$ Hz), 7.06 (d, 18H, $J = 8.9$ Hz), 7.13–7.25 (m, 45H), 7.29–7.43 (m, 78H), 7.63 (m, 18H). ^{13}C NMR ($CDCl_3$) δ 30.7, 51.2, 51.5, 51.8, 69.9, 114.0, 117.9, 118.9, 119.6, 123.2, 125.7, 125.9, 127.5, 127.9, 128.5, 129.2, 129.7, 130.3, 134.0, 136.0, 137.0, 141.2, 145.2, 145.4, 148.3, 149.4, 153.3, 154.9, 156.9, 165.1, 166.8.

[G2]$_3$[C]-(OH)$_6$. 10% Pd/C (50 mg) was added to a solution of **[G1]$_3$[C]** (500 mg, 311 μmol) in a mixed solvent of EtOH (4 ml)/ THF (4 ml). The mixture was flushed three times with hydrogen to remove oxygen and then stirred vigorously at 25°C under hydrogen for 48 h. The reaction mixture was filtered and the filtrate was evaporated to give **[G2]$_3$[C]-(OH)$_6$** (350 mg, 93.6%). ^{1}H NMR (DMSO-d_6) δ 2.05 (s, 9H), 2.20 (s, 3H), 6.68 (d, 12H, $J = 8.6$ Hz), 6.86 (d, 12H, $J = 8.6$ Hz), 7.11–7.20 (m, 18H), 7.24 (d, 3H, $J = 8.4$ Hz), 7.32 (d, 6H, $J = 8.5$ Hz), 7.67 (d, 3H, $J = 7.2$ Hz), 7.80 (dd, 3H, $J = 7.8$,7.9 Hz), 9.29 (s, 6H). ^{13}C NMR (DMSO-d_6) δ 30.3, 50.6, 51.3, 114.6, 118.0, 119.0, 123.8, 126.5, 128.6, 129.2, 129.3, 130.2, 133.9, 136.9, 139.2, 145.0, 149.8, 153.2, 153.7, 155.3, 164.7, 166.4.

[G2]$_3$[C]-(OH)$_{12}$. 10% Pd/C (20 mg) was added to a solution of **[G2]$_3$[C]** (200 mg, 47.5 μmol) in a mixed solvent of EtOH (1.5 ml)/ THF (3 ml). The mixture was reacted according to the procedure for **[G2]$_3$[C]-(OH)$_6$**. The reaction mixture was filtered and the resulting filtrate evaporated to give **[G2]$_3$[C]-(OH)$_{12}$** (130 mg, 81.8%). ^{1}H NMR (DMSO-d_6) δ 2.03 (s, 18H), 2.20 (s, 12H), 6.66 (d, 24H, $J = 8.6$ Hz), 6.84 (d, 24H, $J = 8.6$ Hz), 7.12–7.23 (m, 54H), 7.25 (d, 9H, $J = 8.2$ Hz), 7.30 (d, 12H, $J = 8.5$ Hz), 7.39 (d, 6H, $J = 8.2$ Hz), 7.65 (m, 9H), 7.80 (m, 9H), 9.26 (s, 12H). ^{13}C NMR (DMSO-d_6) 30.3, 30.8, 51.0, 51.8, 114.8, 114.9, 118.4, 119.4, 119.5, 124.1, 125.3, 126.9, 127.2, 129.0, 129.5, 130.2, 130.6, 134.2, 137.3, 139.5, 145.2, 148.7, 150.1, 153.5, 154.0, 155.5, 155.7, 165.0, 165.1, 166.7, 166.8.

[G1]$_3$[C]-(OR)$_6$. To a solution of **[G1]$_3$[C]-(OH)$_6$** (100 mg, 62.3 mmol), 1-hexanol (120 mg, 1.17 mmol), and PPh_3 (300 mg, 1.14 mmol) in dry THF (4 ml) under nitrogen, disopropyl azodicarboxylate (0.24 ml) was added dropwise. The mixture was stirred at 25°C for 24 h and then added to methanol. The precipitate was purified by column chromatography (hexane/CH_2Cl_2 1:6) to give **[G1]$_3$[C]-(OR)$_6$** (120 mg, 92.3%). ^{1}H NMR ($CDCl_3$) δ 0.86 (t, 18H, $J = 8.6$ Hz), 1.27 (m, 24H), 1.46 (m, 12H), 1.79 (m, 12H), 2.12 (s, 9H), 2.21 (s, 3H), 3.91 (t, 12H, $J = 8.6$ Hz), 6.77 (d, 12H, $J = 8.7$ Hz), 7.00 (d, 12H, $J = 8.7$ Hz), 7.05 (d, 6H, $J = 8.7$ Hz), 7.13–7.20 (m, 15H), 7.30 (d, 6H, $J = 8.4$ Hz), 7.63 (m, 6H). ^{13}C NMR ($CDCl_3$) δ 14.0, 22.6, 25.7, 29.3, 29.7, 30.7, 31.6, 51.1, 51.5, 67.9, 113.7, 118.0, 119.0, 119.5, 123.3, 125.6, 129.2, 129.3, 129.6, 130.3, 134.1, 136.1, 140.8, 145.4, 149.6, 153.4, 154.8, 157.2, 165.2, 166.8.

[G2]$_3$[C]-(OR)$_{12}$. This was prepared from **[G2]$_3$[C]-(OH)$_{12}$** (100 mg, 23.8 mmol), 1-hexanol (90 mg, 0.88 mmol), PPh3 (230 mg, 0.87 mmol) and diisopropyl azodicarboxylate (0.18 ml) using the same procedure as for **[G1]$_3$[C]-(OR)$_6$**. The crude product was purified by column chromatography (Benzene/CH_2Cl_2 1:8) to give **[G2]$_3$[C]-(OR)$_{12}$** (115 mg, 92.7%). ^{1}H NMR ($CDCl_3$) δ 0.88 (t, 36H, $J = 8.6$ Hz), 1.42 (m, 24H), 1.74 (m, 24H), 2.12 (s, 18H), 2.22 (s, 12H), 3.91 (t, 24H, $J = 8.6$ Hz),



Scheme 1. Reagent: (i) phenol, CF_3SO_3H; (ii) H_2, Pd/C; (iii) K_2CO_3, benzyl bromide; (iv) Fe, HCl; (v) 3-nitrophthalic anhydride; (vi) compound **2**, $NaOCH_3$.

6.77 (d, 24H, $J = 8.7$ Hz), 6.99 (d, 24H, $J = 8.7$ Hz), 7.07 (m, 18H), 7.13–7.23 (m, 45H), 7.31 (d, 12H, $J = 8.7$ Hz), 7.38 (d, 6H, $J = 8.7$ Hz), 7.62 (m, 18 H). ^{13}C NMR ($CDCl_3$) δ 14.1, 22.7, 25.8, 29.4, 29.8, 30.8, 31.7, 51.2, 51.9, 68.0, 113.8, 118.0, 118.9, 119.1, 119.7, 123.2, 124.1, 125.8, 126.0, 129.4, 129.7, 129.9, 130.5, 134.1, 136.1, 140.9, 145.3, 149.7, 153.4, 155.0, 157.3, 165.3, 166.8, 166.9.

3. Results and discussion

3.1. Synthesis

The general synthetic procedure for the poly(ether–imide) dendrons is shown in Scheme 1. An acid-catalyzed condensation reaction of *p*-nitroacetophenone with excess phenol gave compound **1** [55]. The reduction of the nitro group of **1** with H_2, catalyzed by Pd/C, yielded compound **2**. The latter compound contained an aminophenyl group and two phenolic groups, and served as the building block utilized for the synthesis of the ether–imide dendrimer. Compound **1** was reacted with benzyl bromide in the presence of K_2CO_3 and 18-crown-6 to yield the benzyl ether derivative **3**, which was subsequently reduced with iron to produce **[G1]-NH_2**. The addition of the aminophenyl group of **[G1]-NH_2** to 3-nitrophthalic anhydride, followed by cyclodehydration, led to the corresponding phthalimide **[G1]-NO_2**, [56] which contained an activated nitro functionality located at the focal point of the growing dendritic wedge. The reaction of **[G1]-NO_2** with the phenoxides of

2 gave the next-generation ether–imide **[G2]-NH_2**, [57] which on a second cyclocondensation with 3-nitrophthalic anhydride resulted in the second-generation phthalimide dendron **[G2]-NO_2**. Structures of the phthalimide dendrons and intermediates synthesized were confirmed by ^{1}H NMR, ^{13}C NMR, and high-resolution mass spectrometry. In the ^{1}H NMR spectrum, the dendritic fragment **[G2]-NH_2**, which contained an aminophenyl group at the focal point, shows an AB quartet at 6.66 and 6.89 ppm corresponding to the aromatic protons of the aminophenyl group, and resonances for the aromatic protons of the ether-substituted phthalic rings were located at 7.28–7.44 and 7.62 ppm. The dendritic wedge **[G2]-NO_2**, which contains a 3-nitrophthalimide ring at the focal point, exhibits additional resonances for the aromatic protons of the nitro-substituted phthalic ring at 7.96, 8.14, and 8.20 ppm, while the resonances corresponding to the protons of the aminophenyl group disappeared. These significant differences in resonances allow the focal point group to be identified, the dendrons to be characterized, and their purity to be determined. A comparison of the integration values for these groups to the values for other resonances confirms the generation number as well. ^{13}C NMR also provides complementary information. The resonances assigned to the carbonyl groups of the ether-substituted phthalic rings for **[G2]-NH_2** appeared at 165.1 and 166.7 ppm, while additional resonances corresponding to the carbonyl groups of the nitro-substituted phthalic ring appeared at 161.9 and 164.8 ppm, in the case of **[G2]-NO_2** [56].

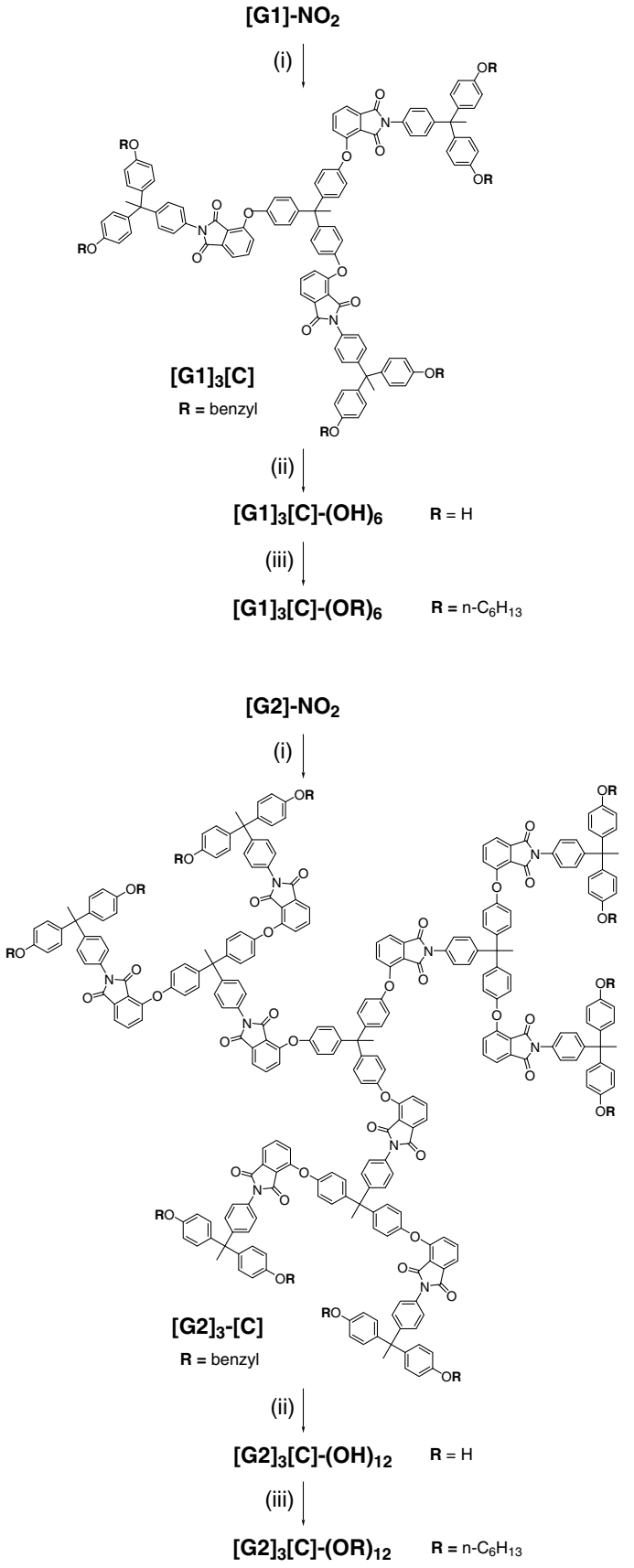
The dendritic wedges obtained were then coupled to a polyfunctional core to yield the dendrimers. Reactions of phenoxide nucleophiles of the core molecule 1,1,1-tris(4-hydroxyphenyl)ethane with nitro-substituted phthalimide dendrons **[G1]-NO_2** and **[G2]-NO_2** gave the ether–imide dendrimers, **[G1]$_3$-[C]** and **[G2]$_3$-[C]**, respectively, as shown in Scheme 2. The benzyl ether groups of ether–imides were selectively removed by catalytic hydrogenolysis without affecting the ether–imide functionalities. Hydrogenolysis of **[G1]$_3$[C]** and **[G2]$_3$[C]** was performed in a mixed solvent of EtOH/THF under an atmosphere of hydrogen using 10 wt% Pd/C as the catalyst to generate dendritic ether–imides **[G1]$_3$[C]-$(OH)_6$** and **[G2]$_3$[C]-$(OH)_{12}$**, respectively, containing 6 and 12 phenolic groups at their periphery. The phenolic-terminated dendrimers were then subjected to chain-end modification via the Mitsunobu reaction by the reaction of its phenolic groups with 1-hexanol in the presence of PPh_3 and diisopropyl azodicarboxylate in dry THF to give the corresponding ether derivatives **[G1]$_3$[C]-$(OR)_6$** and **[G2]$_3$[C]-$(OR)_{12}$**, respectively.

3.2. General characterization of the ether–imide dendrimers

The characterization of the dendrimers was accomplished by a combination of techniques including ^{1}H NMR, ^{13}C NMR, IR, mass spectrometry, and size exclusion chromatography. The attachment of the dendritic wedges to the core molecule was readily followed by the disappearance of the resonances for the protons of the nitro-substituted phthalic ring. Fig. 1 shows the ^{1}H NMR spectra of dendrimers **[G1]$_3$[C]** and **[G2]$_3$[C]**, which have similar features. The peak assignments are based on the peak position of the dendritic intermediates and the auxiliary of 2D (H,H)-COSY spectra. The methylene resonance for the benzyl groups at the periphery of the dendritic structure appeared as a sharp singlet at 5.02 ppm. Resonances associated with the aromatic protons of the phthalimide rings in different layers were indistinguishable. These results are consistent with the highly symmetrical structures of ether–imide dendrimers. Integration of these areas and comparison with each other confirms not only the generation number, but also the number of phthalimide rings on the dendritic macromolecules. Information from ^{13}C NMR spectra added further support for the proposed structure. FTIR spectroscopy also provided complementary evidence for the structures, showing characteristic imide carbonyl absorptions at 1722 and 1776 cm^{-1} for **[G1]$_3$[C]** and at 1724 and 1782 cm^{-1} for **[G2]$_3$[C]** [58].

Removal of the benzyl ether groups was performed by catalytic hydrogenolysis and was easily monitored by the disappearance of the resonances corresponding to the benzyl groups in the ^{1}H NMR spectra. The absence of a resonance at ca. 5.00 ppm for the methylene protons of the benzyl group clearly demonstrates that no residual benzyl groups at the chain ends of the ether–imide dendrimers were presented. Fig. 2 shows the ^{1}H NMR spectra of **[G1]$_3$[C]-$(OH)_6$** and **[G2]$_3$[C]-$(OH)_{12}$**, which contain 6 and 12 phenolic groups, respectively at their peripheries. The aromatic protons of the terminal phenol groups gave rise to an AB quartet at 6.66 and 6.84 ppm. Resonances corresponding to the protons of the phthalimide rings in different layers were indistinguishable and appeared at 7.25, 7.69 and 7.80 ppm. The ratio of integration of these areas correlated well with the expected structures. Concerning the chain-end modification of the phenolic-terminated dendrimers via Mitsunobu etherfication, the resonance for α-CH_2 of the alkyl end groups was observed at 3.91 ppm. The percent functionalization of the terminal groups was determined by comparing the integration ratio of the α-CH_2 attributed to the alkyl end groups versus those from the aromatic units. The use of excess reagents (3.0 equiv. per phenol group) resulted in complete (95–100%) functionalization, indicating that the hydroxyl groups at the chain ends are readily accessible to the reagents in solution.

Size-exclusion chromatography (SEC) proved to be useful in analysing the purity and polydispersity of the dendrimers. Since the ether–imide dendrimers were prepared by stepwise, controlled processes, each compound was predicted to be monodisperse. Table 1 illustrates the results of SEC measurements that were calibrated against narrow-dispersity poly(methyl methacrylate) standards to give M_n and polydispersity data of the dendrimers. The



Scheme 2. Reagent: (i) 1,1,1-tris(4-hydroxyphenyl)ethane, $NaOCH_3$; (ii) H_2, Pd/C; (iii) 1-hexanol/THF, PPh_3, DIAD.

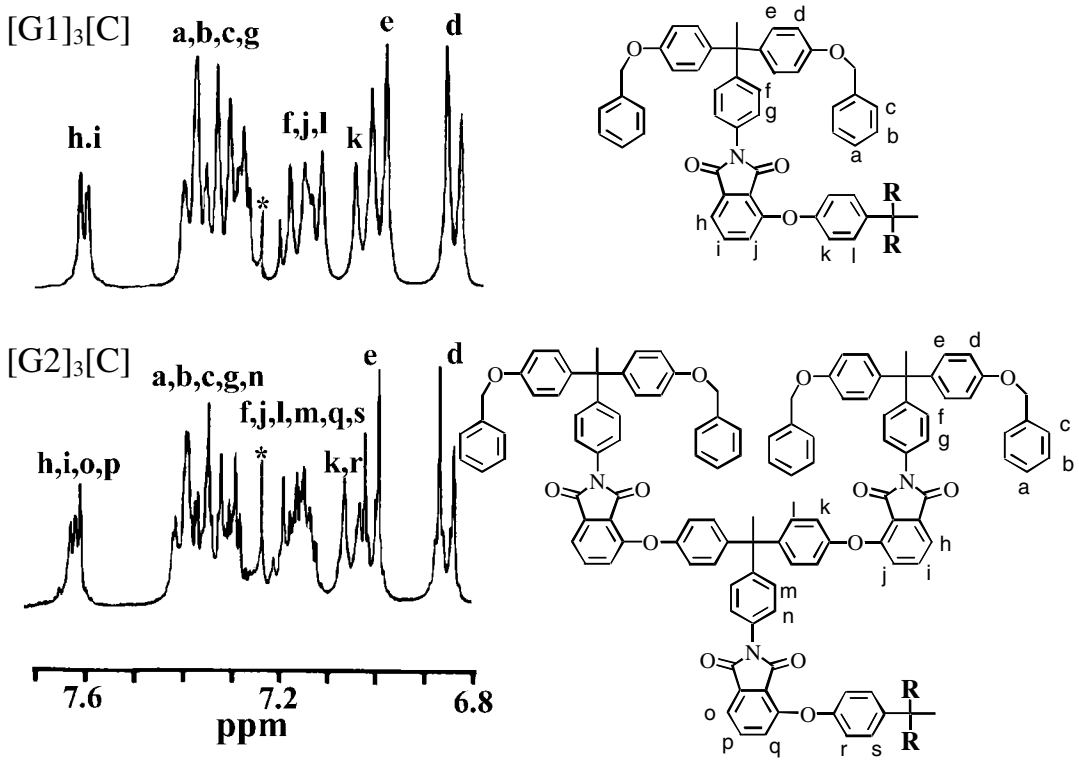


Fig. 1. 300-MHz ^{1}H NMR spectra in the region of 6.8–7.7 ppm for **[G1]$_3$[C]** and **[G2]$_3$[C]** in $CDCl_3$. * — signal due to $CDCl_3$.

molecular weights of the ether–imide dendrimers were underestimated by a factor of 1.3–2.5. This factor increases with the growth of generations. Due to the highly branched, compact structures of these dendritic macromolecules in comparison with the coiled conformation of the linear polymer standards, SEC measurements tended to underestimate their true molecular weight [59,60]. The SEC chromatograms of the second-generation dendritic poly(ether–imide)s are shown in Fig. 3. All the ether–imide dendrimers gave narrow, single-peak symmetrically shaped chromatograms and showed no evidence of an unresolved shoulder. This result revealed that these dendritic macromolecules were pure and had a narrow distribution of molecular weights.

Matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF-MS) is an attractive alternative to mass analysis of the ether–imide dendrimers. This technique provides higher mass determinations for intact molecular ions of nonvolatile species and is particularly useful for structural characterization of high molecular weight dendrimers [61–68]. The method is based on the laser desorption of molecules dissolved in a suitable matrix. Results of MALDI-TOF-MS spectrometry of the ether–imide dendrimers are shown in Table 1. Fig. 4 shows the

Table 1
SEC and MALDI-TOF-MS data of the ether–imide dendrimers

Dendrimer	M_w (calcd.)	M_w (SEC)	PDI[a]	Molecular ion obs.	Mass[b] (calcd.)	Mass (measured)
[G1]$_3$[C]	2148	1328	1.05	$[M + K]^{+c}$	2186.6	2186.8
[G2]$_3$[C]	5289	2574	1.08	$[M + K]^{+c}$	5328.2	5324.7
[G1]$_3$[C]-(OH)$_6$	1607	1223	1.02	$[M + K]^{+c}$	1645.8	1644.6
[G2]$_3$[C]-(OH)$_{12}$	4208	2738	1.07	$[M + K]^{+c}$	4246.7	4253.4
[G1]$_3$[C]-(OR)$_6$	2112	1105	1.02	$[M + K]^{+d}$	2219.6	2225.4
[G2]$_3$[C]-(OR)$_{12}$	5218	2028	1.08	$[M + K]^{+d}$	5325.4	5323.4

[a] Polydispersity data.
[b] Weighted isotopic average.
[c] Matrix: 2,5-dihydroxybenzoic acid.
[d] Matrix: retinoic acid.

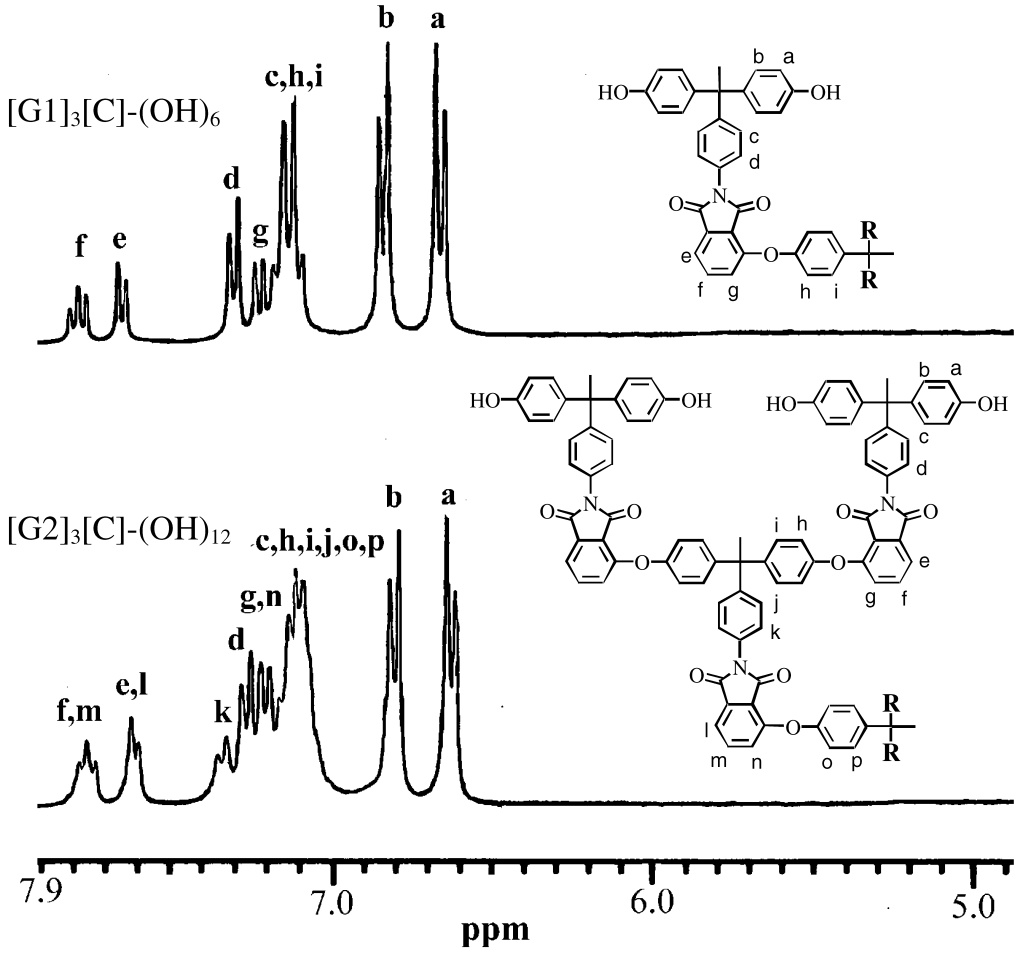


Fig. 2. 300-MHz ^{1}H NMR spectra in the region of 4.9–7.9 ppm for **[G1]$_3$[C]-(OH)$_6$** and **[G2]$_3$[C]-(OH)$_{12}$** in DMSO-d_6.

MALDI spectra of the second-generation ether–imide dendrimers. The dominant signals observed are either potassium or silver adducts of the molecular ions, depending on the matrix used. These peaks occurred at *m*/*z* values consistently within 0.2% of the theoretical values. Thus, the MALDI spectra data provided additional support for the identity of these ether–imide dendrimers. It could also be concluded that these dendrimers are pure and monodisperse.

3.3. Characterization of physical properties

Previous experimental and theoretical studies have shown that the glass transition temperature (T_g) of dendritic macromolecules depends mainly on the internal monomer units and the polarity and number of the end groups [69–71]. The T_gs of these dendritic ether–imides, as determined by differential scanning calorimetry (DSC), are presented in Table 2. For dendrimers with identical terminal functionality, T_g

Table 2
Effect of the functionality of the chain ends on the thermal and solution properties of the dendritic poly(ether–imide)s. Solubility: +, soluble; + −, partially soluble; −, insoluble

Dendrimer	T_g (°C)	Solubility in Toluene	CH_2Cl_2	$CHCl_3$	THF	DMF	DMSO	CH_3OH/ 1 N $NaOH_{(aq)}$[a]
[G1]$_3$[C]	120	+	+	+	+	+	+ −	−
[G2]$_3$[C]	159	+	+	+	+	+	+ −	−
[G1]$_3$[C]-(OH)$_6$	190	−	−	−	+	+	+	+
[G2]$_3$[C]-(OH)$_{12}$	210	−	−	−	+	+	+	+
[G1]$_3$[C]-(OR)$_6$	76	+	+	+	+	+	−	−
[G2]$_3$[C]-(OR)$_{12}$	93	+	+	+	+	+	−	−

[a] Volume ratio 1:1.

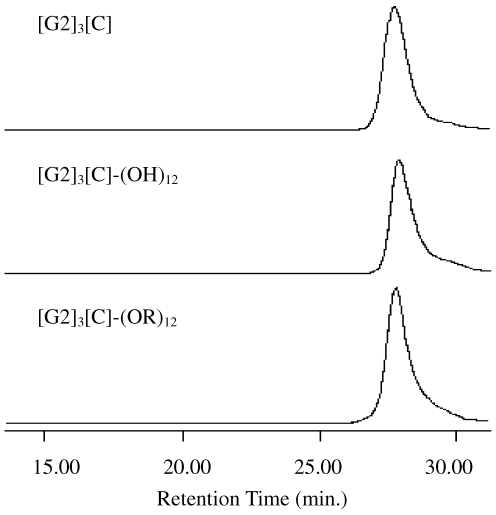


Fig. 3. SEC traces for the second-generation ether–imide dendrimers.

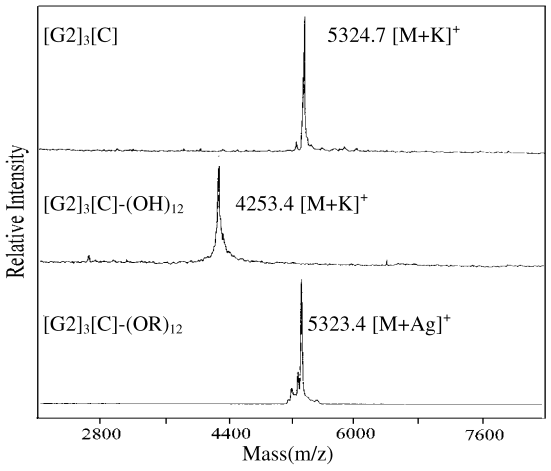


Fig. 4. MALDI-TOF mass spectra of **[G2]$_3$[C]**, **[G2]$_3$[C]-(OH)$_{12}$** and **[G2]$_3$[C]-(OR)$_{12}$**.

increases with increasing molecular weight. Within the same generation, the value of T_g for the ether–imides increases with increasing chain-end polarity. For the second-generation dendritic ether–imide, an increase in the end group polarity from *n*-hexyl ether to benzyl ether to a hydroxyl group results in an increase in T_g from 93 to 159 to 210°C. The relatively high T_g of **[G2]$_3$[C]-(OH)$_{12}$** is probably a reflection of the hydrogen-bonding capability of the phenolic terminal groups.

Because of their highly branched structures, these dendritic ether–imides have enhanced solubility in organic solvents and are highly soluble in solvents such as THF and DMF. However, the different end groups also lead to differences in solubility, as shown in Table 2. The ether-terminated dendrimers are soluble in relatively nonpolar solvents such as toluene, CH_2Cl_2 and $CHCl_3$, but are insoluble or partially soluble in DMSO. In contrast, the phenolic-terminated dendrimers are soluble in DMSO but insoluble in relatively nonpolar solvents. In addition, the phenolic-terminated dendrimers are soluble in a mixed solvent of $NaOH_{(aq)}/CH_3OH$ due to the acidic nature of phenolic groups.

4. Summary

Dendritic ether–imide macromolecules with modifiable chain ends were synthesized by the stepwise convergent growth approach using 1-(4-aminophenyl)-1,1-bis(4-hydroxyphenyl)ethane **2** as the building block. The synthetic sequence for the ether–imide dendrons was based on (i) the aromatic nucleophilic substitution of an activated nitro group with a phenoxide nucleophile to form the ether linkage [57], and (ii) the condensation of the aminophenyl group with nitro-substituted phthalic anhydride, followed by ring-closure to yield the imide ring, which contained the reactive nitro functionality [56]. Through aromatic nucleophilic displacement, the dendritic wedges with an activated nitro group were coupled to the polyfunctional core, 1,1,1-tris(4-hydroxyphenyl)ethane, to give the dendritic poly(ether–imide)s. The subsequent selective removal of the benzyl ether chain ends by catalytic hydrogenolysis yielded dendrimers with phenolic chain ends. Further modification of the chain ends was readily accomplished by Mitsunobu etherification [53]. The synthetic strategy employed here provides a clear demonstration of the protection–deprotection approach for the modification of the chain ends of dendritic macromolecules. The effect of the chain-end functional group on the physical properties of these ether–imide dendrimers was also investigated. The nature of the end groups was found to strongly influence the thermal and solution behavior of the various surface-modified dendrimers. We are currently extending the use of compound **2** as the structural component in the one-step synthesis of hyperbranched poly(ether–imide)s [72] as well as in the preparation of poly(ether–imide) dendrimers via the orthogonal coupling approach [73,74].

Acknowledgements

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References

[1] Tomalia DA, Naylor AM, Goddard III WA. Angew Chem, Int Ed Engl 1990;29:138.
[2] Mekelburger H-B, Jaworek W, Vögtle F. Angew Chem, Int Ed Engl 1992;31:1571.
[3] Fréchet JMJ. Science 1994;263:1710.
[4] Newkome GR, editor. Advances in dendritic molecules, 1. Greenwich, CT: JAI Press, 1994.
[5] Newkome GR, Moorefield CN, Vögtle F. Dendritic molecules: concepts, syntheses, perspectives. Weinheim: VCH, 1996.

[6] Zeng F, Zimmerman SC. Chem Rev 1997;97:1681.
[7] Frey H, Lach C, Lorenz K. Adv Mater 1998;10:279.
[8] Smith DK, Diederich F. Chem Eur J 1998;4:1353.
[9] Chow H-F, Mong TK-K, Nongrum MF, Wan C-W. Tetrahedron 1998;54:8543.
[10] Selby TD, Blackstock SC. J Am Chem Soc 1998;120:12155.
[11] Chaumette JL, Laufersweiler MJ, Parquette JR. J Org Chem 1998;63:9399.
[12] Leininger S, Stang PJ, Huang SP. Organometallics 1998;17:3981.
[13] Busson P, Ihre H, Hult A. J Am Chem Soc 1998;120:9070.
[14] Miller LL, Kunugi Y, Canavesi A, Rigaut S, Moorefield CN, Newkome GR. Chem Mater 1998;10:1751.
[15] Balogh L, Tomalia DA. J Am Chem Soc 1998;120:7355.
[16] Bliznyuk VN, Rinderspacher F, Tsukruk VV. Polymer 1998;39:5249.
[17] Stewart GM, Fox MA. Chem Mater 1998;10:860.
[18] Tomioka N, Takasu D, Takahashi T, Aida T. Angew Chem, Int Ed Engl 1998;37:1531.
[19] Trollsäs M, Hedrick JL. J Am Chem Soc 1998;120:4644.
[20] Leduc MR, Hayes W, Fréchet JMJ. J Polym Sci, Part A: Polym Chem 1998;36:1.
[21] Yamakawa Y, Ueda M, Takeuchi K, Asai M. J Polym Sci, Part A: Polym Chem 1999;37:3638.
[22] Liu MJ, Kono K, Fréchet JMJ. J Polym Sci, Part A: Polym Chem 1999;37:3492.
[23] Sato T, Jiang DL, Aida T. J Am Chem Soc 1999;121:10658.
[24] Piotti ME, Rivera Jr F, Bond R, Hawker CJ, Fréchet JMJ. J Am Chem Soc 1999;121:9471.
[25] Vögtle F, Plevoets M, Nieger M, Azzellini GC, Credi A, De Cola L, De Marchis V, Venturi M, Balzani V. J Am Chem Soc 1999;121:6290.
[26] Pillow JNG, Halim M, Lupton JM, Burn PL, Samuel IDW. Macromolecules 1999;32:5985.
[27] Vassilev K, Ford WT. J Polym Sci, Part A: Polym Chem 1999;37:2727.
[28] Chechik V, Zhao MQ, Crooks RM. J Am Chem Soc 1999;121:4910.
[29] Kriesel JW, Tilley TD. Chem Mater 1999;11:1190.
[30] Zhao MQ, Crooks RM. Adv Mater 1999;11:217.
[31] Haba O, Haga K, Ueda M, Morikawa O, Konishi H. Chem Mater 1999;11:427.
[32] Astruc D. Acc Chem Res 2000;33:287.
[33] Weener JW, Meijer EW. Adv Mater 2000;12:741.
[34] McElhanon JR, McGrath DV. J Org Chem 2000;65:3525.
[35] Malenfant PRL, Fréchet JMJ. Macromolecules 2000;33:3634.
[36] Pan YJ, Ford WT. Macromolecules 2000;33:3731.
[37] Gong AJ, Liu CY, Chen YM, Chen CF, Xi F. Polymer 2000;41:6103.
[38] Ishida Y, Jikei M, Kakimoto M. Macromolecules 2000;33:3202.
[39] Balzani V, Ceroni P, Gestermann S, Kauffmann C, Gorka M, Vögtle F. J Chem Soc, Chem Commun 2000:853.
[40] Kriesel JW, Tilley TD. Chem Mater 2000;12:1171.
[41] Morikawa A, Ono K. J Polym 2000;32:234.
[42] Ruckenstein E, Yin WSJ. J Polym Sci, Part A: Polym Chem 2000;38:1443.
[43] Pan YJ, Ford WT. J Polym Sci, Part A: Polym Chem 2000;38:1533.
[44] Lupton JM, Hemingway LR, Samuel IDW, Burn PL. J Mater Chem 2000;10:867.
[45] Nlate S, Ruiz J, Blais JC, Astruc D. J Chem Soc,Chem Commun 2000:417.
[46] Tomalia DA, Baker H, Dewald J, Hall M, Kallos G, Martin S, Roeck J, Ryder J, Smith P. J Polym 1985;17:117.
[47] Newkome GR, Yao Z-Q, Baker GR, Gupta VK. J Org Chem 1985;50:2003.
[48] Hawker CJ, Fréchet JMJ. J Am Chem Soc 1990;112:7638.
[49] Xu ZF, Moore JS. Angew Chem, Int Ed Engl 1993;32:1354.
[50] Miller TM, Neenan TX. Chem Mater 1990;2:346.
[51] Henrik I, Hult A, Fréchet JMJ, Gitsov I. Macromolecules 1998;31:4061.
[52] Hawker CJ, Fréchet JMJ. J Chem Soc, Perkin Trans 1992;1:2459.
[53] Mitsunobu O. Synthesis 1981;1.
[54] Leu CM, Chang YT, Shu CF, Teng CF, Shiea J. Macromolecules 2000;33:2855.
[55] Morgan PW. Macromolecules 1970;3:536.
[56] White DM, Takekoshi T, Williams FH, Relles HM, Donahue PE, Klopfer HJ, Louks GR, Manello JS, Matthews RO, Schluenz RW. J Polym Sci, Polym Chem Ed 1981;19:1635.
[57] Williams FJ, Donahue PEJ. Org Chem 1977;42:3414.
[58] Hsiao SH, Li CT. J Polym Sci, Part A: Polym Chem 1999;37:1403.
[59] Lorenz K, Mülhaupt R, Frey H, Rapp U, Mayer-Posner FJ. Macromolecules 1995;28:6657.
[60] Hawker CJ, Fréchet JMJ. J Chem Soc, Chem Commun 1990:1010.
[61] Walker KL, Kahr MS, Wilkins CL, Xu Z, Moore JS. J Am Soc Mass Spectrum 1994;5:731.
[62] Newkome GK, Guther R, Moorefield CN, Gardullo F, Echegoyen L, Pérez-Cordero E, Luftmann H. Angew Chem, Int Ed Engl 1995;34:2023.
[63] Kawaguchi T, Walker KL, Wilkins CL, Moore JS. J Am Chem Soc 1995;117:2159.
[64] Leon JW, Kawa M, Fréchet JMJ. J Am Chem Soc 1996;118:8847.
[65] Wu ZC, Biemann K. Int J Mass Spectromet 1997;165:349.
[66] Krska SK, Seyferth D. J Am Chem Soc 1998;120:3604.
[67] Morikawa A, Ono K. Macromolecules 1999;32:1062.
[68] Yu D, Valdimirov N, Fréchet JMJ. Macromolecules 1999;32:5186.
[69] Wooley KL, Hawker CJ, Pochan JM, Fréchet JMJ. Macromolecules 1993;26:1514.
[70] Danusso F, Levi M, Gianotti G, Turri S. Polymer 1993;34:3687.
[71] Stutz H. J Polym Sci, Part B: Polym Phys 1995;33:333.
[72] Thompson DS, Markoski LJ, Moore J. Macromolecules 1999;32:4764.
[73] Zeng F, Zimmerman SC. J Am Chem Soc 1996;118:5326.
[74] Deb SK, Maddux TM, Yu L. J Am Chem Soc 1997;119:9079.