# Synthesis of Dendritic Polyamides *via* a Convergent Growth Approach

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The synthesis of dendritic polyamides by the convergent growth approach is described. The synthesis involves an $A_2B$ monomer, *N*-(*tert*-butoxycarbonyl)iminodipropionic acid, containing two free carboxylic acid groups and a protected amine. The polycondensation reaction is carried out using classical peptide chemistry with sequential coupling–deprotection steps to afford polyamides with molecular weights up to 5000. As their size increases, the dendritic polyamide find their growth restricted by steric problems. The final step of growth is the condensation of the dendrimers with a trifunctional acid chloride core to give the final globular polyamides. The macromolecules were characterised by a variety of chromatographic and spectroscopic techniques, and were found to have precisely defined structures.

Dendritic macromolecules are fractal structures[1,2] that emanate from a central core. The occurrence of a branch point at each monomer unit contributes to the distinct structure of the dendritic polymers which are believed to adopt a globular or even spherical shape as their molecular weight increases. Their compact structure is somewhat analogous to that of naturally occurring globular proteins. In addition to being highly branched, the dendritic polymers also contain a large number of chain ends per macromolecule. It is the combination of these features that is mainly responsible for the overall properties of the novel polymers.

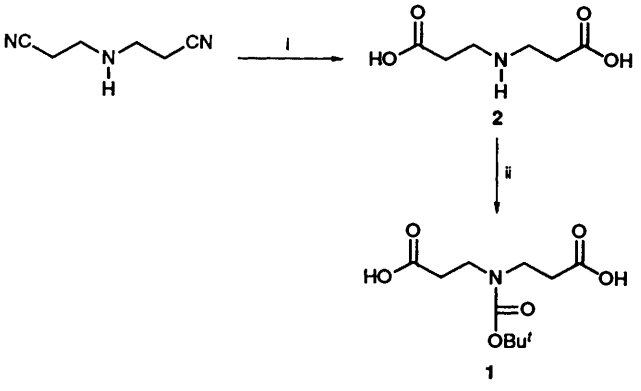
All early syntheses of dendritic macromolecules have been accomplished by a divergent growth scheme[1–6] in which the synthesis begins at a polyfunctional core and proceeds radially 'outwards' by successive addition of layers of monomeric units with a branch point occurring at each monomer unit. This method is characterised by a rapid increase in the number of chain ends as the macromolecule grows. Therefore, generation growth requires the reaction of a large number of functional groups of the macromolecule with the monomer. There are several examples of polymers made by this approach: cascade molecules,[1] poly(amidoamines),[2] polyethers,[3] polyamides,[4] poly(arylamines)[5] and poly(amidoalcohols).[6]

More recently, an alternate 'convergent' synthetic route has been developed that differs from the divergent approach in two significant ways. First, the synthesis begins at the latent periphery or chain-ends of the macromolecule and proceeds 'inwards' towards a single central functional group or focal point. Secondly, only a few functional groups, typically three, are involved in generation growth at any stage of the synthesis. This is in contrast with the divergent approach in which the number of reactive groups increase geometrically as the reaction proceeds. The convergent growth approach has been used to make polyethers,[7] poly(aramides),[8] polyphenylenes[8,9] and polyesters.[10]

We report here the first example of the use of a convergent growth methodology for the preparation of a series of monodispersed, aliphatic dendrimers containing symmetrical amide linkages. The coupling of these dendritic fragments to a trifunctional core molecule and the characterisation of the globular polymers will also be described.

## Results and Discussion

The strategy was to use a simple, symmetrical monomer to which we could apply basic peptide coupling chemistry. The monomer chosen was *N*-(*tert*-butoxycarbonyl)iminodipropionic acid, **1**. With this system, two carboxylic acid functionalities are available for the condensation step, while the protected amine is readily activated for the second coupling step with another monomer unit. Monomer **1** was synthesised in two steps: quantitative hydrolysis of commercially available 3,3′-iminodipropionitrile with barium hydroxide gave the diacid **2** which was then protected as its *t*-BOC carbamate using di-*tert*-butyl dicarbonate to give **1** in 60% yield (Scheme 1).

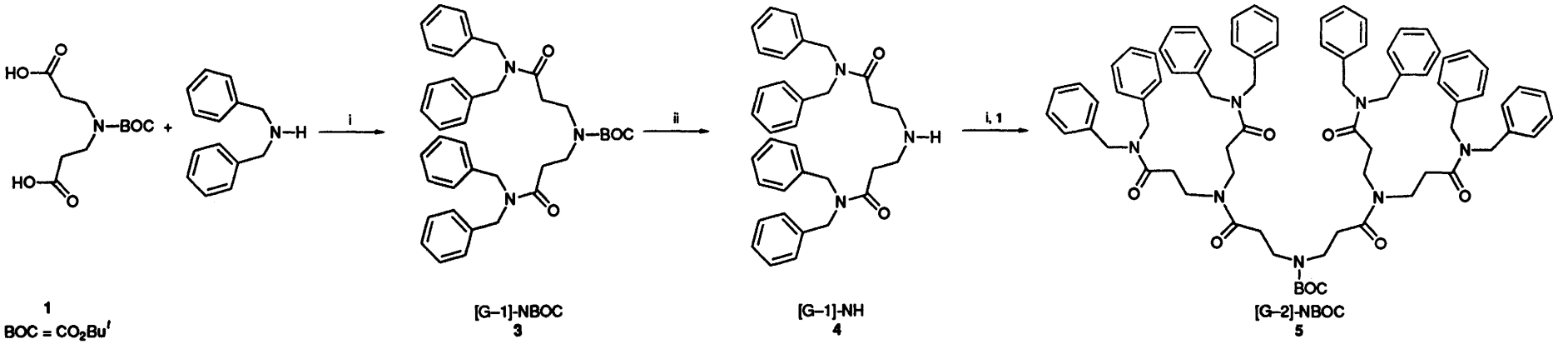



**Scheme 1** *Reagents:* i, $Ba(OH)_2$, $H_2O$; ii, NaOH, Bu$^t$OH, $O(CO_2Bu^t)_2$

1,3-Dicyclohexylcarbodiimide (DCC), a commonly used peptide coupling agent, was used to effect condensation of the acid functionalities of the monomer with the amino group of two growing dendrimer molecules. 4-Dimethylaminopyridine (DMAP) in catalytic quantities was also used since its presence has been shown to result in increased yields of peptides in coupling reactions.[11] More specifically, the use of DMAP has been shown to enhance the coupling efficiency of sterically hindered amino acids where reactions are usually slow and incomplete.

*Synthesis of Dendritic Polyamides.*—An outline of the polyamide synthesis is shown in Scheme 2. The condensation of the diacid **1** with an excess of dibenzylamine (3.3 equiv.) in the presence of DCC (2.5 equiv.) and DMAP (0.1 equiv.) gave the first generation compound **3**, also denoted as [G-1]-NBOC, in 81% yield. The *t*-BOC amino protecting group was then removed by using a large excess (50 equiv.) of trifluoroacetic acid (TFA) to give the first generation amine **4** in 94% yield.

The newly generated amino group of dendrimer **4** can then be coupled with monomer **1** in the presence of DCC to give dendrimer [G-2]-NBOC **5** in 82% yield. Removal of the *t*-BOC group of compound **5** with TFA afforded dendrimer **6** with a free amino group in 95% yield.



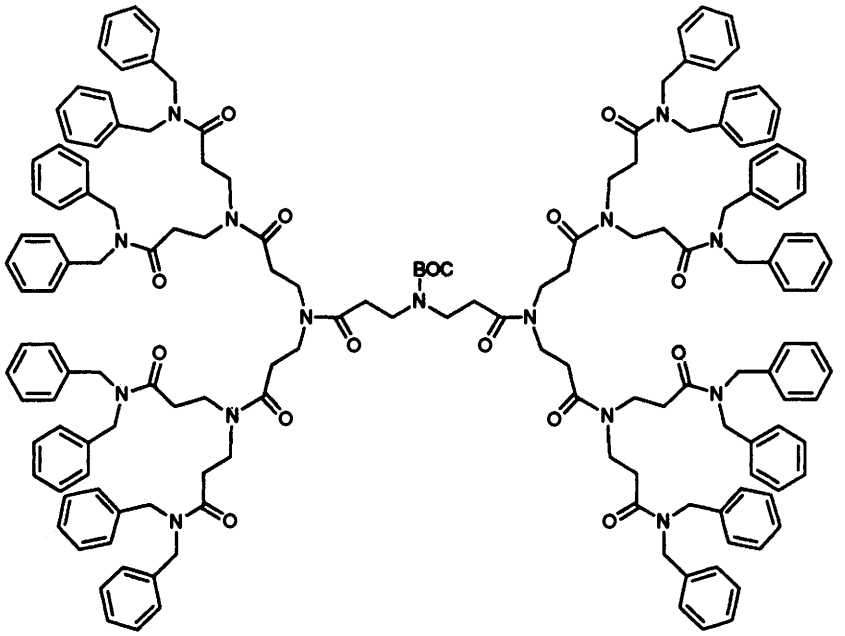

1
BOC = $CO_2Bu^t$

[G–1]-NBOC
3

[G–1]-NH
4

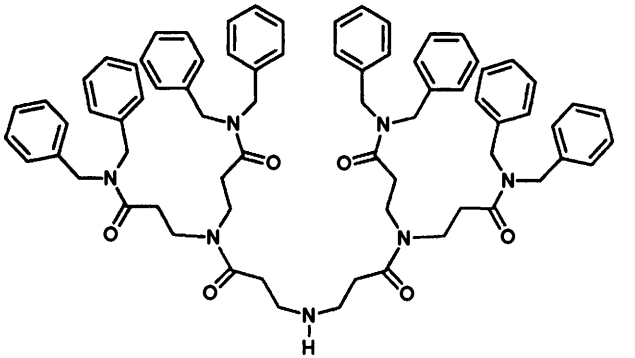
[G–2]-NBOC
5

ii

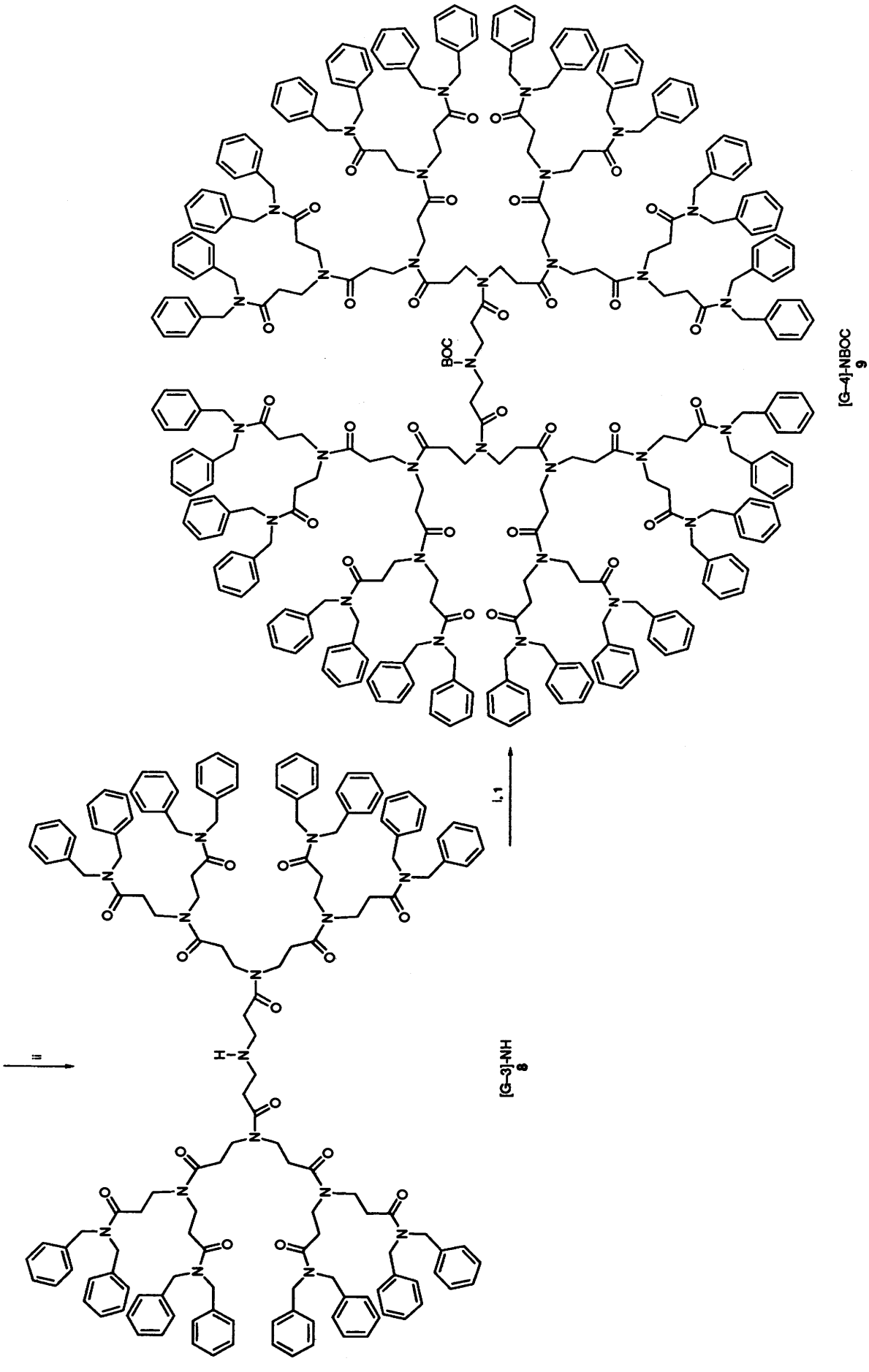



[G–3]-NBOC
7

i, 1



[G–2]-NH
6




**Scheme 2** *Reagents*: i, DCC, DMAP; ii, TFA

Condensation of compound **6**, [G-2]-NH, with monomer **1** afforded the third generation dendrimer **7** in 87% yield. This reaction was more difficult to achieve than previous amidation reactions and required the addition of a further 2.5 equiv. of DMAP to effect the coupling in satisfactory fashion. Deprotection of dendrimer [G-3]-NBOC **7** gave the third generation amine **8** in 85% yield.

The third generation amine **8** was coupled with monomer **1** to afford the fourth generation dendrimer **9** which could not be isolated in pure form. Although the dendrimer [G-4]-NBOC **9** and the monofunctionalised product, in which only one acid functionality of the monomer had reacted, could be differentiated using gel permeation chromatography (GPC), they could not be separated by standard chromatographic methods. Even with an excess of amine **8** (8.5 equiv.), DCC (2.5 equiv.) and DMAP (2.5 equiv.), the coupling reaction could not be pushed to completion. The GPC trace of the reaction mixture indicated that approximately 65% of the reaction mixture is the diamidated product and 35% is the monofunctionalised compound. As [G-4]-NBOC **9** could not be purified by flash chromatography or precipitation, further growth to afford higher molecular weight polyamides was not attempted.

Steric congestion of the free amine of dendrimer **8** may be responsible for the decrease in its ability to condense with monomer **1**. The steric inhibition of these polyamides at this stage in their synthesis may originate from the geometrical restrictions imposed by the amide bonds, as the high barrier to rotation about the C–N bond leads to a relatively rigid structure.[12] The bulkiness of the numerous phenyl rings on the periphery of the dendrimers may also contribute to the steric congestion of the dendritic fragments. The efficiency of the separation of the dendritic polymers from the reaction mixture is influenced by the molecular weight of the polyamides, as well as the effectiveness of the coupling reaction. As the polyamides increase in molecular weight, repeated separations by flash chromatography must be performed in order to purify the dendrimers. The removal of the DCC by-product, dicyclohexylurea (DCU), becomes particularly difficult with an increase in molecular size. It appears that there is an enhanced ability to confine impurities, such as DCU and solvent molecules, within the dendritic structure with an increase in molecular weight.

The dendrimers containing the free amino functionality were coupled to a polyfunctional core unit in order to explore the reactivities of the focal group of the dendrimers and to obtain rapidly higher molecular weight polymers from the available polyamides (Scheme 3). The trifunctional compound, benzene-1,3,5-tricarbonyl trichloride **10**, was chosen because of its high reactivity towards amines. In a test experiment, the core molecule **10** (1.0 equiv.) was coupled to an excess (3.2 equiv.) of dibenzylamine in the presence of an excess (3.2 equiv.) of triethylamine to give the dendrimer $[G\text{-}0]_3$-C **11** in 83% yield. The first generation amine **4** was condensed with monomer **1** in a similar fashion to afford $[G\text{-}1]_3$-C **12** in 52% yield while the second generation amine **6** afforded $[G\text{-}2]_3$-C **13** with molecular weight 3650 in 78% yield (Scheme 3).

The condensation of the third generation amine **8** with the trifunctional core **10** does not afford the desired triamidated product $[G\text{-}3]_3$-C but mainly the difunctionalised molecule $[G\text{-}3]_2$-C-$CO_2H$ **14** in which only two dendritic fragments have become attached to the core. Monitoring of the coupling reaction by GPC reveals the importance of stoichiometry and confirms that the steric requirements for the attachment of the molecules of amine **8** to the core **10** exceed the capabilities of the approach.

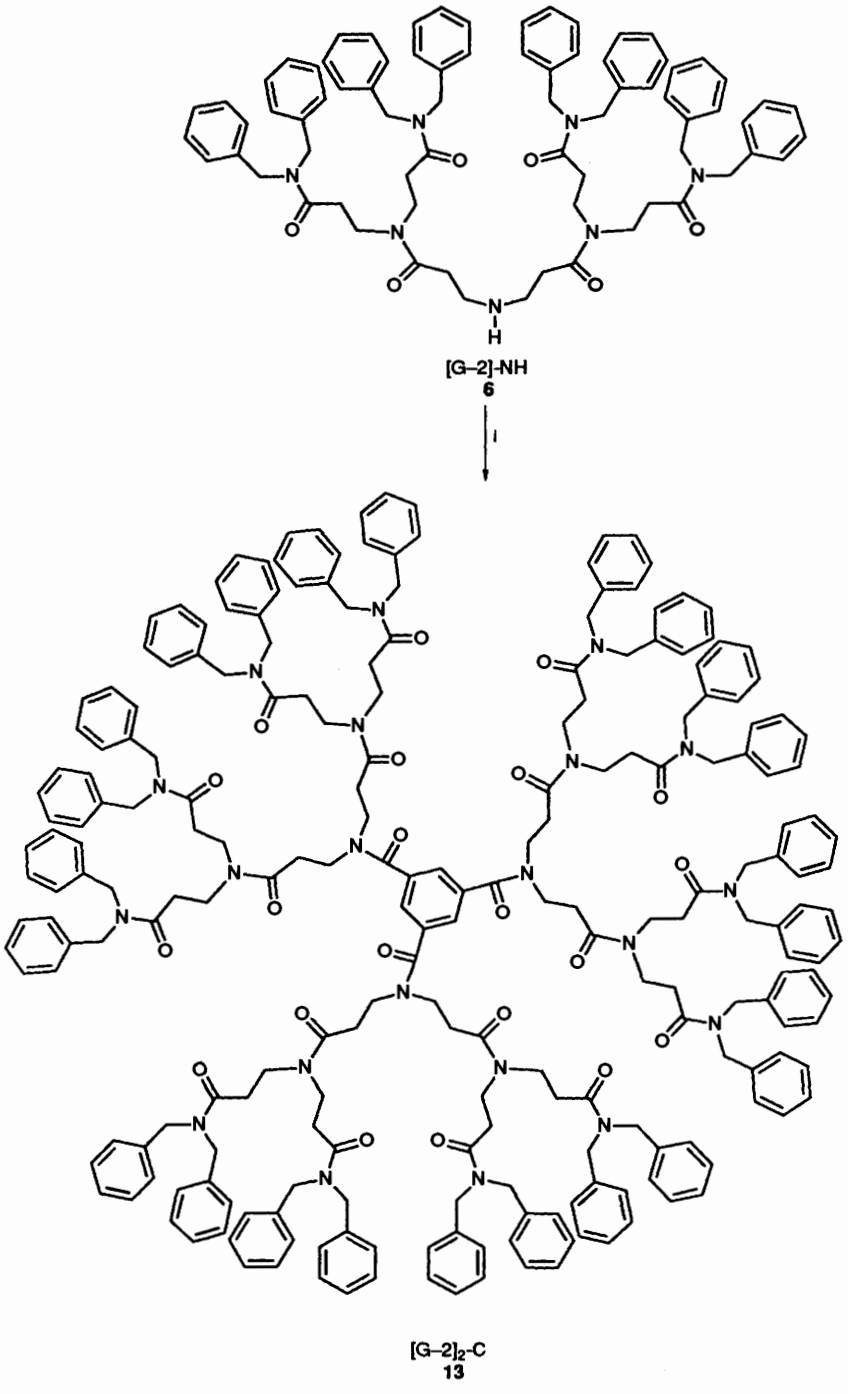
With a 3:1 molar ratio of compounds **8** to **10**, three peaks are seen corresponding to unchanged starting materials and the mono- and di-amide derivatives of benzene-1,3,5-tricarboxylic acid. If a 4.5:1 ratio of compounds **8** to **10** is used, only two peaks are seen corresponding to unchanged amine **8** and the bis-amidated compound $[G\text{-}3]_2$-C-$CO_2H$ **14**. IR spectrometry confirms that compound **14** retains a free carboxylic acid group with O–H and C=O stretches of 3100 and 1740 $cm^{-1}$, respectively. In addition, $^{13}C$ NMR spectrometry shows that a free carboxylic acid remains with the carbonyl carbon at 172 ppm. The yield of compound **14** (81%) suggests that coupling of two molecules of the third generation amine **8** is relatively easy while serious steric inhibition prevents the formation of the fully amidated core.

This steric inhibition to dendritic growth is not unexpected for molecules prepared by the convergent approach. The inability of [G-3]-NH **8** to react with the three acyl groups of **10** and the slow and difficult formation of [G-4]-NBOC **9** by reaction of [G-3]-NH **8** with monomer **1** confirm this limitation of the convergent approach. Additional problems may arise from the amide coupling chemistry itself. However, other structures such as polyethers[7] and polyesters[10] appear to be less sensitive to steric inhibition of growth in early generations and the advantages of the convergent approach in the preparation of well-defined architectures is well documented.

*Characterisation.*—The high symmetry of the polyamides made verification of their structures by $^1H$ NMR spectroscopy particularly simple (Fig. 1). For the *t*-BOC protected dendrimers, there are five regions of interest in the $^1H$ NMR spectra: (1) the methyl protons of the *t*-BOC group at 1.3 ppm; (2) the methylene protons adjacent to the carbonyl of an amide group at 2.6 ppm; (3) the methylene protons adjacent to the nitrogen of an amide group at 3.6 ppm; (4) the benzylic protons, split by the amide, near 4.4 and 4.5 ppm; and (5) the aromatic protons from 7.0–7.3 ppm. As the molecular weight of the dendritic macromolecule increases, the peaks in the $^1H$ NMR spectra broadened while the splitting patterns of the benzylic protons becomes more complex.

The generation number or size of the polyamides can be readily determined by integration of the $^1H$ NMR spectral peaks of the BOC-protected macromolecules. For example, in the second generation compound **5** there are nine methyl protons for the *t*-BOC group (1.39 ppm) relative to the 16 benzylic protons (4.41–4.58 ppm) in the $^1H$ NMR spectrum (Fig. 1). In comparison, note that there are nine methyl protons for the *t*-BOC group (1.3 ppm) and 32 benzylic protons in the third generation compound **7**. The ratio of the methyl protons of the *t*-BOC group relative to the benzylic protons, aromatic protons or aliphatic protons provides the generation number of the dendritic polyamides. The ratio of the nine *t*-BOC methyl protons to the benzylic protons in the $^1H$ NMR spectrum distinguishes between the desired bis-amidated product and the monofunctionalised product, in which only one of the two carboxylic acid groups of the monomer had reacted. This technique proves useful in the detection of incomplete reaction of the dendritic fragments with the monomer.

The NMR spectra are useful in the evaluation of cleavage of the *t*-BOC group. In general, the proton and carbon NMR spectra of the dendrimers with the free amino groups are similar to the spectra of the BOC-protected dendrimers. A comparison of the $^1H$ NMR spectra of the second generation dendrimers **5** and **6** is shown in Fig. 1. The methyls of the *t*-BOC group of compound **5** resonate at 1.3 ppm. After treatment with TFA, no residual BOC groups are seen in the $^1H$ NMR spectrum of compound **6**. The carbons for the BOC group which resonate at 28.5, 79.8 and 155.2 ppm in the $^{13}C$ NMR spectrum of compound **5** are not present in the spectrum of the second generation amine **6**. As further verification of the cleavage of the *t*-BOC group, IR spectroscopy confirms the presence (or absence) of free amine seen as a peak at 3330 $cm^{-1}$.




**Scheme 3** *Reagents:* i, $NEt_3$, **10**

The $^{13}C$ NMR spectra are consistent with $^1H$ NMR spectra of the polyamides. In the compounds containing a protected amine, the carbons for the *t*-BOC group resonate at 28.5, 79.8 and 155.2 ppm. The methylene carbons α to the carbonyl group are observed at 31–32 ppm while the methylene carbons α to the amide nitrogens are seen at 42–45 ppm. The signal for the benzylic carbons is located at 48–50 ppm, the aromatic carbons at 126–129 ppm and 136–137 ppm, and the carbonyl carbons of the amides at 170–172 ppm.

Although NMR spectroscopy is invaluable in the characterisation of the polyamides, IR spectroscopy proved to be the easiest method for the detection of side products in the coupling reactions in which DCC was involved. The mono-amidated compound, in which only one of the two carboxylic acid groups of the monomer had reacted, can be readily differentiated from the difunctionalised product by IR spectroscopy, as the O–H stretch for the uncharged carboxylic acid of the monofunctionalised product is seen as a broad absorption peak around 3000 $cm^{-1}$.

Proton NMR spectroscopy is also useful to confirm the structures of the dendrimers coupled to the trifunctional core. The $^1H$ NMR spectra are similar to those of the dendritic amines, except for the additional aromatic peaks of the core molecule seen as a sharp signal which is slightly downfield from the broader signal for the phenyl protons. Integration of the signals for the benzylic protons relative to the aromatic protons can give an indication of the generation number or size of the polyamide. For example, in the first generation compound **3** there are eight benzylic protons (4.2–4.5 ppm) relative to the three aromatic protons of the core unit (7.3 ppm) and the 20 aromatic protons of the phenyl groups (6.9–7.3 ppm).

GPC of the products showed narrow single peaks for each

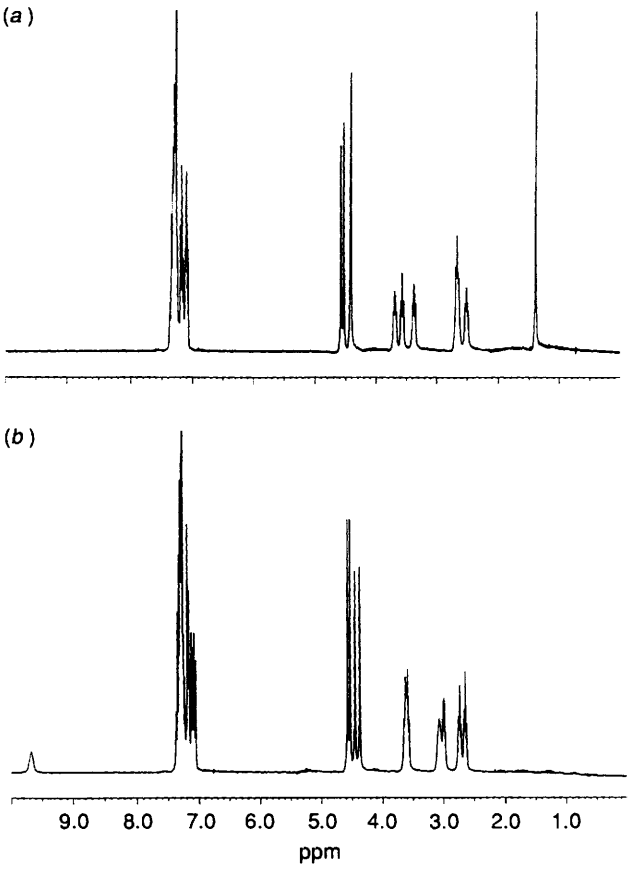



**Fig. 1** $^1$H NMR spectra of the second generation dendrimers (*a*) [G-2]-NBOC **5** and (*b*) [G-2]-NH **6**

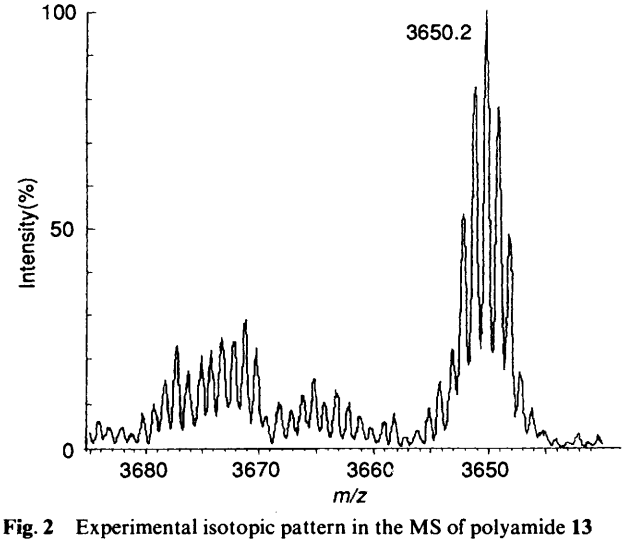



**Fig. 2** Experimental isotopic pattern in the MS of polyamide **13**

pure compound, although the peaks for the free amines were somewhat broadened. It has been reported previously[7] that the molecular weight of dendritic macromolecules as measured by GPC is much smaller than the actual value due to the globular shape of the macromolecules. In view of the relatively small size of the molecules reported herein, with molecular weights frequently close to the calibration limit of the columns (1200 a.m.u.), the GPC chromatograms were mainly used to confirm the purity of the molecules being prepared and their narrow size distribution.

A comparison of the theoretical molecular weights with the absolute molecular weights of the dendritic polyamides as determined by MS, using the fast atom bombardment (FAB) method, is given in Table 1. The mass spectra exhibited a clean parent ion for each dendrimer. In addition, the isotopic patterns of these polyamides were identical with the theoretical isotopic patterns thus verifying the monodisperity of the polymers. The experimental isotopic pattern for a polyamide with molecular formula $C_{231}H_{244}N_{21}O_{21}$ is shown in Fig. 2. The series of peaks in the higher molecular weight region are due to the presence of a sodium adduct of the polyamide, a common phenomenon in the mass spectra of amide-containing compounds[13] while no lower molecular weight impurities are seen.

The glass transition temperatures of the polyamides increased with an increase in molecular weight, or size (Table 2). Glass transition temperatures below 40 °C are consistent with those of other polyamides, such as poly(γ-benzyl-L-glutamate) which has a glass transition temperature of 15 °C.

## Conclusions

Monodispersed dendritic polyamides can be synthesised by a convergent growth approach to afford macromolecules with well-defined structures as characterised by various chromatographic and spectroscopic techniques. Our studies have shown that the reactivity of the focal amine of the third generation dendrimer **8** was decreased due to steric inhibition. This, coupled to purification problems, prevented the preparation of larger dendritic polyamide structures based on the iminodipropionic acid building block.

Although DMAP was used in anticipation of steric inhibition,[11] the complications of the polyamide synthesis was probably related to the coupling reagent (DCC) employed. Conversion of the acid group of monomer **1** into an activated ester[12] as an alternative to the use of a coupling agent might be preferable for the preparation of larger, dendritic polyamides.

## Experimental

*General Directions.*—IR spectra were recorded on a Nicolet IR/44 spectrophotometer as thin films of KBr disks. $^1$H NMR spectra were recorded on solutions in $CDCl_3$ or [$^2H_6$]acetone on a Brüker WM300 (300.13 MHz) spectrometer using the solvent proton signal as the reference. $^{13}$C NMR spectra were recorded at 75 MHz on a Brüker WM300 spectrometer on solutions in $CDCl_3$ with the solvent carbon signal as the standard. Mass spectra were obtained on a Kratos MS890 with FAB ionization in a matrix of 3-nitrobenzyl alcohol.

Analytical TLC was performed on commercial Merck plates coated with silica gel $GF_{254}$ (0.25 mm thick). Silica for flash chromatography was Merck Kieselgel 60 (230–400 mesh). GPC was carried out on a Nicolet LC/9560 liquid chromatograph connected to a Milton Roy refractoMonitor IV refractive index detector with data analysis performed using Viscotek GPC-PRO software. Five PLgel GPC/SEC columns (type B to F) connected in series were used with tetrahydrofuran (THF) as solvent. Columns were calibrated using narrow dispersity polystyrene standards. Differential scanning calorimetry was carried out on a Mettler DSC 30. Benzyl bromide and dichloromethane were purified by distillation.

N-(tert-*Butoxycarbonyl*)*iminodipropionic Acid* **1**.—A solution of 3,3′-iminodipropionic acid (12.8 g, 79.6 mmol) in water (75 $cm^3$) was treated with NaOH solution (1.7 mol $dm^{-3}$; 100 $cm^3$) and Bu$^t$OH (100 $cm^3$), followed by the dropwise addition of di-*tert*-butyl dicarbonate (18.3 $cm^3$, 79.7 mmol). The reaction mixture was kept at 45 °C for 22 h, filtered and washed with hexane (× 3). The aqueous portion was acidified to pH 1 and extracted with dichloromethane (× 3). The organic portion was washed with water (× 2) and brine, dried ($MgSO_4$) and

**Table 1** Theoretical molecular weights of the polyamides as compared to the molecular weights determined by GPC and MS

| Compound | | Theoretical | $M_w$ (GPC) | $M_n$ (GPC) | ($MH^+$) (MS) |
|---|---|---|---|---|---|
| [G-1]-NBOC | **3** | 619.8 | — | — | 620.4 |
| [G-2]-NBOC | **5** | 1264.6 | 800 | 800 | 1265.6 |
| [G-3]-NBOC | **7** | 2554.2 | 1000 | 1000 | — |
| [G-4]-NBOC | **9** | 5133.5 | 1400 | 1300 | — |
| [G-1]-NH | **4** | 519.7 | — | — | 520.5 |
| [G-2]-NH | **6** | 1164.5 | 1400 | 1300 | 1164.8 |
| [G-3]-NH | **8** | 2454.1 | 2000 | 1800 | — |
| $[G\text{-}0]_3$-C | **11** | 747.9 | — | — | 748.8 |
| $[G\text{-}1]_3$-C | **12** | 1715.2 | 1000 | 1000 | 1715.8 |
| $[G\text{-}2]_3$-C | **13** | 3649.6 | 1500 | 1500 | 3650.2 |
| $[G\text{-}3]_2$-C-$CO_2H$ | **14** | 5082.3 | 2200 | 2100 | — |

**Table 2** Glass transition temperatures for the polyamides

| Compound | | $T_m$/°C | $T_g$/°C |
|---|---|---|---|
| [G-1]-NBOC | **3** | — | −27 |
| [G-1]-NH | **4** | — | −2 |
| [G-2]-NBOC | **5** | — | −10 |
| [G-2]-NH | **6** | — | 17 |
| [G-3]-NBOC | **7** | — | 29 |
| [G-3]-NH | **8** | — | 27 |
| $[G\text{-}0]_3$-C | **11** | 120 | — |
| $[G\text{-}1]_3$-C | **12** | — | 16 |
| $[G\text{-}2]_3$-C | **13** | — | 38 |

evaporated to dryness to give the title acid **1** as a white solid (56%); $\nu$/cm$^{-1}$ 3000, 2980, 1650, 1600, 1410, 1370 and 1260; $\delta_H(CDCl_3)$ 1.44 (s, 9 H, $CH_3$), 2.62 (t, 4 H, $CH_2CO$), 3.52 (t, 4 H, $CH_2N$) and 11.66 (br, 2 H, $CO_2H$); $\delta_C(CDCl_3)$ 30.7 ($CH_3$), 33.5 ($CH_2CO$), 43.9 ($CH_2N$), 80.4 ($CCH_3$), 155.2 and 176.1 (C=O) (Calc. for $C_{11}H_{19}NO_6$: C, 50.6; H, 7.3; N, 5.4. Found: C, 50.67; H, 7.35; N, 5.52%).

*General Procedure for Amide Formation Using DCC.*[14]—Monomer **1** (1.0 equiv.), DCC (2.5 equiv.) and DMAP (0.1 equiv.) dissolved in the minimum amount of dry dichloromethane was treated with a dendritic amine (2.5 equiv.) and the reaction mixture was stirred under nitrogen at room temperature. The mixture was filtered, washed with HCl (0.5 mol dm$^{-3}$), saturated aqueous $NaHCO_3$, and brine. The organic portion was dried ($MgSO_4$) and evaporated to dryness. The crude product was purified as outlined in the following text.

*General Procedure for Amine Deprotection.*[14]—The protected amine of the polyamide (1.0 equiv.) was treated with TFA (50 equiv.) and the reaction mixture was stirred at room temperature. It was then evaporated to remove the excess of TFA, redissolved in dichloromethane, neutralized by triethylamine, and washed with water (× 3). The organic portion was dried ($MgSO_4$) and evaporated to dryness.

*Condensation with Core Molecule.*—The free amine (3.5 equiv.) and triethylamine (3 equiv.) in the minimum amount of dry dichloromethane was treated with benzene-1,3,5-tricarbonyl trichloride **11**. The reaction mixture was stirred under nitrogen at room temperature and then washed with HCl (0.1 mol dm$^{-3}$; × 3), aqueous $NaHCO_3$ (5%; × 2) and brine. The organic portion was dried ($MgSO_4$) and evaporated to dryness. The crude product was purified as outlined in the following text.

[G-1]-NBOC **3**.—This compound was prepared from dibenzylamine and monomer **1** and purified (after 21 h) by flash chromatography eluting with $CH_2Cl_2$ and gradually increasing to 10% MeOH–$CH_2Cl_2$ to give the title compound **3** as a clear oil (81%); $\nu$/cm$^{-1}$ 2980, 1690, 1650, 1450, 1410, 1370 and 1170; $\delta_H(CDCl_3)$ 1.33 (s, 9 H, $CH_3$), 2.65 (t, 4 H, $CH_2CO$), 3.56 (t, 4 H, $CH_2N$), 4.45 (br, 4 H, PhC$H_2$), 4.55 (br 4 H, PhC$H_2$) and 7.13–7.42 (m, 20 H, Ar$H$); $\delta_C(CDCl_3)$ 28.4 ($CH_3$), 32.2, 32.7 ($CH_2CO$), 44.6, 44.9 ($CH_2N$), 48.2, 49.8, 50.0 (Ph$CH_2$), 79.7 ($CCH_2$) 126.4, 126.5, 127.4, 127.5, 127.6, 127.7, 128.2, 128.6, 128.7, 129.0 (Ar$CH$), 136.1, 136.4, 137.1, 137.2 (Ar$C$), 155.3, 171.6 and 171.8 (C=O); $m/z$ (FAB) 620.4.

[G-1]-NH **4**.—This preparation starting from compound **3** gave the title compound **4** (after 2 h) as a light yellow solid (94%); $\nu$/cm$^{-1}$ 3330, 1690, 1680, 1450, 1200, 1170 and 1130; $\delta_H(CDCl_3)$ 2.90 (t, 4 H, $CH_2CO$), 3.20 (t, 4 H, $CH_2N$), 4.37 (s, 4 H, PhC$H_2$), 4.56 (s, 4 H, PhC$H_2$) and 7.1–7.3 (m, 20 H, Ar$H$); $\delta_C(CDCl_3)$ 29.0 ($CH_2CO$), 44.6 ($CH_2N$), 48.4, 49.7 (Ph$CH_2$), 126.4, 127.6, 127.9, 128.4, 128.7, 129.1 (Ar$CH$), 135.3, 136.2 (Ar$C$) and 171.0 (C=O); $m/z$ (FAB) 520.5.

[G-2]-NBOC **5**.—This compound was prepared from compound **4** and monomer **1** and purified (after 45 h) by flash chromatography eluting with ethyl acetate–hexane (1:1) and gradually increasing to ethyl acetate to give the title compound **5** as a clear, glassy solid (82%); $\nu$/cm$^{-1}$ 2980, 1650, 1460, 1370, 1220 and 1180; $\delta_H(CDCl_3)$ 1.39 (s, 9 H, $CH_3$), 2.53 (t, 6 H, $CH_2CO$), 2.66 (t, 6 H, $CH_2CO$), 3.37 (t, 4 H, $CH_2N$), 3.57 (t, 4 H, $CH_2N$), 3.69 (t, 4 H, $CH_2N$), 4.41 (s, 8 H, PhC$H_2$), 4.53 (s, 4 H, PhC$H_2$), 4.58 (s, 4 H, PhC$H_2$) and 7.1–7.4 (m, 40 H, Ar$H$); $\delta_C(CDCl_3)$ 28.5 ($CH_3$), 31.5, 31.8 ($CH_2CO$), 42.8, 43.6, 44.4, 44.7 ($CH_2N$), 48.0, 48.4, 48.8, 49.8, 49.9 (Ph$CH_2$), 79.7 ($CCH_3$), 126.2, 126.4, 126.5, 126.6, 127.4, 127.5, 127.6, 127.8, 128.1, 128.2, 128.6, 128.9, 129.1 (Ar$CH$), 136.1, 136.2, 136.3, 137.0, 137.1 (Ar$C$), 155.2, 170.7, 171.2, 171.6, 171.7, 171.8 and 172.7 (C=O); $m/z$ (FAB) 1265.6; GPC: $M_w$ = 800, $M_n$ = 800.

[G-2]-NH **6**.—This preparation starting from compound **5** gave the title compound **6** (after 7 h) as a clear, glassy solid (95%); $\nu$/cm$^{-1}$ 3330, 1690, 1440, 1200 and 1130; $\delta_H(CDCl_3)$ 2.67 (t, 4 H, $CH_2CO$), 2.74 (t, 4 H, $CH_2CO$), 3.00 (br, 4 H, $CH_2CO$), 3.07 (br, 4 H, $CH_2N$), 3.59 (t, 4 H, $CH_2N$), 3.63 (t, 4 H, $CH_2N$), 4.37 (s, 4 H, PhC$H_2$), 4.45 (s, 4 H, PhC$H_2$), 4.53 (s, 4 H, PhC$H_2$), 4.57 (s, 4 H, PhC$H_2$), 7.05–7.38 (m, 40 H, Ar$H$) and 9.65 (br, NH); $\delta_C(CDCl_3)$ 31.3, 31.5 ($CH_2CO$), 42.1, 42.8, 44.3, 44.5 ($CH_2N$), 48.1, 48.6, 49.8, 50.0 (Ph$CH_2$), 126.3, 126.5, 127.4, 127.5, 127.6, 127.7, 128.1, 128.2, 128.6, 128.7, 128.9, 129.1 (Ar$CH$), 136.1, 136.2, 136.8, 137.0 (Ar$C$), 170.6, 170.7 and 171.4 (C=O); $m/z$ (FAB) 1164.8; GPC: $M_w$ = 1400, $M_n$ = 1300.

[G-3]-NBOC **7**.—This compound was prepared from com-

pound **6** and monomer **1** and purified (after 96 h) by flash chromatography eluting with $CH_2Cl_2$ and gradually increasing to 10% MeOH–$CH_2Cl_2$ to give the title compound **7** as a clear, glassy solid (87%); $\nu$/cm$^{-1}$ 1650, 1450, 1220 and 1180; $\delta_H$($CDCl_3$) 1.3 (s, 9 H, $CH_3$), 2.50 (m, 12 H, $CH_2CO$), 2.65 (m, 16 H, $CH_2CO$), 3.40 (m, 6 H, $CH_2N$), 3.45 (m, 6 H, $CH_2N$), 3.55 (m, 8 H, $CH_2N$), 3.65 (m, 8 H, $CH_2N$), 4.40 (s, 16 H, PhC$H_2$), 4.55 (s, 16 H, PhC$H_2$) and 7.07–7.35 (m, 80 H, Ar$H$); $\delta_C$($CDCl_3$) 28.4 ($CH_3$), 31.2, 31.3, 31.4, 31.9, 32.0, 32.1, 32.3 ($CH_2CO$), 42.4, 42.7, 44.0, 44.3, 44.5 ($CH_2N$), 47.9, 48.0, 48.4, 48.6, 49.0, 49.8, 49.9, 50.0, 51.5, 51.7, 53.4 (Ph$CH_2$), 79.8 ($CCH_3$), 126.1, 126.2, 126.4, 127.3, 127.4, 127.5, 127.6, 127.8, 128.0, 128.1, 128.5, 128.6, 128.9, 129.0 (Ar$CH$), 136.1, 136.2, 136.3, 136.9, 137.0, 137.1 (Ar$C$), 155.1, 170.5, 170.6, 171.0, 171.2, 171.4, 171.5 and 172.3 (C=O); GPC: $M_w$ = 2000, $M_n$ = 1800 (Calc. for $C_{159}H_{177}N_{15}O_{16}$: C, 74.8; H, 7.0; N, 8.2. Found: C, 74.51; H, 7.24; N, 8.30%).

[G-3]-NH **8**.—This preparation starting from **7** gave **8** (after 7 h of reaction) as a yellow, glassy solid (93%); $\nu$/cm$^{-1}$ 3330, 1680, 1460, 1200 and 1160; $\delta_H$($CDCl_3$) 2.51 (t, 4 H, $CH_2CO$), 2.63 (t, 20 H, $CH_2CO$), 2.87 (br, 4 H, $CH_2$), 2.95 (br, 4 H, $CH_2$), 3.43 (t, 8 H, $CH_2N$), 3.54 (t, 8 H, $CH_2N$), 3.61 (t, 8 H, $CH_2N$), 4.39 (d, 12 H, PhC$H_2$), 4.44 (s, 4 H, PhC$H_2$), 4.54 (m, 16 H, PhC$H_2$) and 7.0–7.3 (m, 80 H, Ar$H$); $\delta_C$($CDCl_3$) 31.3, 31.9, 32.1, 32.3, 33.9 ($CH_2CO$), 42.4, 42.7, 44.3, 44.5 ($CH_2N$), 48.0, 48.5, 48.8, 49.8, 50.0, 50.1, 51.6 (Ph$CH_2$), 126.1, 126.2, 126.5, 127.4, 127.5, 127.6, 127.7, 128.1, 128.2, 128.6, 128.7, 128.9, 129.1 (Ar$CH$), 136.1, 136.2, 136.9, 137.1 (Ar$C$) and 170.3, 170.7, 171.3 and 171.5 (C=O); GPC: $M_w$ = 1000, $M_n$ = 1000 (Calc. for $C_{154}H_{169}N_{15}O_{14}$: C, 75.4; H, 6.9; N, 8.6. Found: C, 75.08; H, 7.37; N, 8.57%).

[G-0]$_3$-C **11**.—This compound was prepared from dibenzylamine and purified (after 2 h) by chromatography eluting with $CH_2Cl_2$ and gradually increasing to 5% MeOH–$CH_2Cl_2$ to give the title compound **11** as a white solid (83%); $\nu$/cm$^{-1}$ 1650, 1450, 1410 and 1240; $\delta_H$($CDCl_3$) 4.16 (s, 6 H, PhC$H_2$), 4.63 (s, 6 H, PhC$H_2$), 7.0–7.3 (m, 30 H, Ar$H$) and 7.64 (s, 3 H, Ar$H$); $\delta_C$($CDCl_3$) 47.5, 51.5 (Ph$CH_2$), 126.2, 127.0, 127.6, 128.5, 128.9, 136.0, 136.5, 137.0 (Ar$CH$ and Ar$C$) and 170.4 (C=O); $m/z$ (FAB) 748.4.

[G-1]$_3$-C **12**.—This compound was prepared from **4** and purified (after 48 h) by chromatography eluting with diethyl ether and gradually increasing to 10% MeOH–diethyl ether to give **12** as a clear, glassy solid (52%); $\nu$/cm$^{-1}$ 1650, 1500, 1470, 1450 and 1210; $\delta_H$($CDCl_3$) 2.19 (t, 6 H, $CH_2CO$), 2.73 (t, 6 H, $CH_2CO$), 3.59 (t, 6 H, $CH_2N$), 3.72 (t, 6 H, $CH_2N$), 4.20 (s, 6 H, PhC$H_2$), 4.33 (s, 12 H, PhC$H_2$), 4.46 (s, 6 H, PhC$H_2$) and 6.9–7.3 (m, 63 H, Ar$H$); $\delta_C$($CDCl_3$) 31.3, 32.2, 33.9 ($CH_2CO$), 42.5, 46.0 ($CH_2N$), 48.0, 48.2, 49.0, 49.9 (Ph$CH_2$), 126.4, 127.3, 127.6, 128.2, 128.6, 128.9, 136.0, 136.5, 137.0 (Ar$CH$ and Ar$C$), 170.0 and 171.3 (C=O); $m/z$ (FAB) 1715.8; GPC: $M_w$ = 1000, $M_n$ = 1000.

[G-2]$_3$-C **13**.—This compound was prepared from compound **6** and purified (after 16 h) by chromatography eluting with 5% MeOH–$CH_2Cl_2$ to give the title compound **13** as a clear, glassy solid (78%); $\nu$/cm$^{-1}$ 1640, 1470, 1450 and 1210; $\delta_H$($CDCl_3$) 2.4–2.9 (br, 36 H, $CH_2CO$), 3.4–3.8 (br, 36 H, $CH_2N$), 4.3–4.7 (m, 48 H, PhC$H_2$) and 7.0–7.6 (m, 123 H, Ar$H$); $\delta_C$($CDCl_3$) 30.6, 31.2, 31.3, 31.9 ($CH_2CO$), 42.0, 42.6, 44.4; 45.4 ($CH_2N$), 48.3, 48.4, 49.7, 49.9 (Ph$CH_2$), 125.2, 125.9, 126.3, 126.4, 127.3, 127.5, 127.6, 128.1, 128.2, 128.5, 128.8, 136.1, 136.2, 136.9, 137.1 (Ar$CH$ and Ar$C$), 169.8, 170.6, 170.7, 170.8 and 171.4 (C=O); $m/z$ (FAB) 3650.2; GPC: $M_w$ = 1500, $M_n$ = 1500.

[G-3]$_2$-C-$CO_2$H **14**.—This compound was prepared from compound **8** and purified (after 17 h) by chromatography eluting with 10% MeOH–$CH_2Cl_2$ to give the title compound **14** as a yellow solid (81%); $\nu$/cm$^{-1}$ 3100, 1740, 1640, 1460 and 1210; $\delta_H$($CDCl_3$) 2.4–2.9 (br, 56 H, $CH_2CO$), 2.9–3.3 (br, 8 H, $CH_2N$), 3.3–4.0 (br, 48 H, $CH_2N$), 4.3–4.8 (br, 64 H, PhC$H_2$) and 7.0–7.7 (br, 160 H, Ar$H$); $\delta_C$($CDCl_3$) 30.7, 31.4, 31.9, 32.0, 32.2, 32.8, 33.6 ($CH_2CO$), 42.4, 44.2, 44.4 ($CH_2N$), 48.0, 48.4, 48.8, 49.4, 49.8, 50.1, 51.6, 51.9 (Ph$CH_2$), 126.1, 126.2, 126.3, 126.4, 127.4, 127.5, 127.6, 127.7, 128.0, 128.1, 128.5, 128.6, 128.9, 129.0 (Ar$CH$), 136.1, 136.2, 136.9, 137.1 (Ar$C$), 170.3, 170.6, 170.8, 171.2, 171.4 and 172.1 (C=O); GPC: $M_w$ = 2200, $M_n$ = 2100 (Calc. for $C_{317}H_{340}N_{30}O_{32}$: C, 74.9; H, 6.7; N, 8.3. Found: C, 74.83; H, 6.79; N, 8.22%).

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