

A simple 'one pot' route to the hyperbranched analogues of Tomalia's poly(amidoamine) dendrimers

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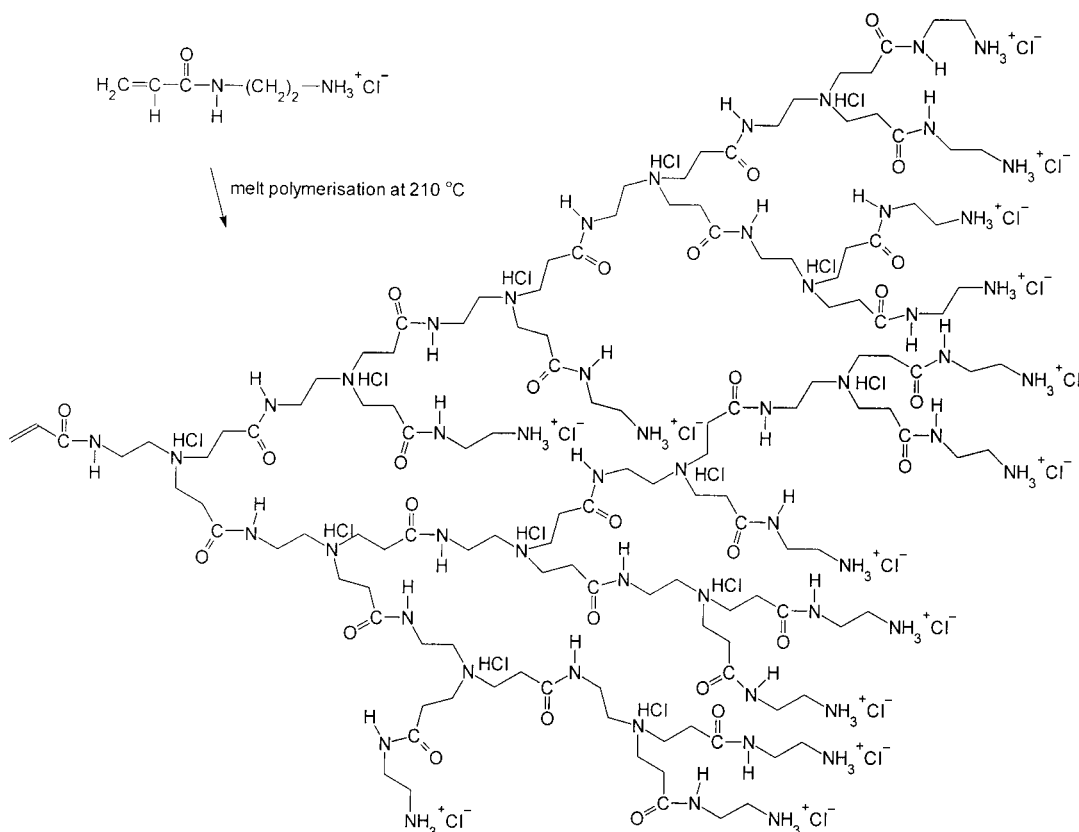
Melt polymerisation of *N*-acryloyl-1,2-diaminoethane hydrochloride gives the hyperbranched hydrochloride salt analogues of Tomalia's poly(amidoamine) dendrimers, for which spectroscopic analysis establishes a branching ratio close to one.

Scientific and technological interest in dendrimers grew rapidly following Tomalia's stimulating review,¹ but bulk applications remain inhibited by the labour intensive syntheses involved. A characterising feature of dendritic polymers is that, past a critical point, their intrinsic viscosity decreases with increasing molecular weight.² This contrasts with linear and lightly branched polymers and has potential technological implications. It would be attractive to mimic this unusual molecular weight-viscosity behaviour in more readily accessible materials.

As part of a programme of research into the synthesis and properties of AB_n hyperbranched polymers we have studied the melt polymerisation of *N*-acryloyl- α,ω -diaminoalkane hydrochlorides, H₂C=CHCONH(CH₂)_nNH₃⁺Cl⁻, (*n* = 2–7). The monomers, produced by a straightforward protection/deprotection strategy,³ polymerised, *via* a Michael addition process, on heating at 210 °C under nitrogen. The products, water soluble

polyelectrolytes, had the same elemental analysis as the monomers. Variation of the polymethylene spacer length (*n* = 2–7) had a marked effect on both monomer reactivity (*e.g.* *n* = 2 reacts much faster than *n* = 6) and the structure and properties of the polymer. The process is summarised in Scheme 1 for the case where *n* = 2.

¹H and ¹³C NMR spectroscopy unambiguously demonstrated the loss of the acrylamide vinyl unit and generation of new methylene units during polymerisation, and allowed an estimation of the number average molecular weight (*M*_n) based on end group counting. The *M*_n values obtained would be over-estimates if significant cyclisation through the focal acrylate group had occurred. Aqueous gel permeation chromatography of these polyelectrolytes was uninformative, but MALDI-TOF mass spectrometry (2,5-dihydroxybenzoic acid matrix, Kratos Kompact MALDI IV in linear detection mode) showed a series of ions corresponding to degrees of polymerisation (dp) in the range 2 to 38. In the spectrum reproduced in Fig. 1, recorded for the polymer derived from *N*-acryloyl-1,6-diaminohexane hydrochloride (*n* = 6), the major ion sequence corresponds to the simple multiple addition products detected as mono-protonated oligomers of the free base. The minor series, 55 mass units behind the parent ions, corresponds to loss of the focal



Scheme 1

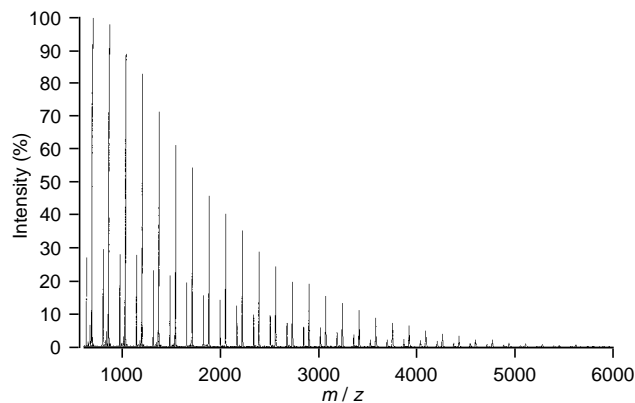


Fig. 1 MALDI-TOF mass spectrum of the polymer prepared from *N*-acryloyl-1,6-diaminohexane hydrochloride ($n = 6$) recorded using MALDI 4 with pulsed extraction

$\text{CH}_2=\text{CHCO}$ unit or to one part of a process of random amide link fragmentation. The comparative intensity of this minor series increases with increasing laser power. However, the absence of the other fragment expected from a random cleavage at amide links leads us to favour the first postulate. In further support of this view we observe that under conditions which favour fragmentation, both of the expected series of ions from random fragmentation at amide bonds can be seen.

Analysis of this spectrum using the Kompact software gave a value of 1500 for M_n of the free base, which compared well with the value of 1570 calculated from the ^1H NMR spectrum. The intensity distribution of peaks in Fig. 1 qualitatively resembles the distribution predicted by Flory,⁴ but careful quantitative analysis shows that in these cases the MALDI-TOF technique fails to provide a representative picture of the whole sample, this is particularly evident when considering materials of broader polydispersity and produced at higher degrees of conversion.⁵

Michael addition polymerisation of these monomers can, in principle, yield secondary or tertiary amines corresponding to linear or branched sub-units. Thus amide and primary (terminal, T), secondary (linear, L) and tertiary (branched, B) amine nitrogen environments are possible. The frequency of the branched and terminal groups is connected, $T = B + 1$. ^{15}N NMR spectroscopy, recorded quantitatively in natural abundance, revealed three signals; the amide and primary amine nitrogens are readily identified on the basis of chemical shift (relative to liquid ammonia) and literature assignments of related compounds,⁶ but the signals for amine nitrogens in linear and branched units overlap; however, integration allows an assignment of the extent of branching.

Thus, for polymers derived from *N*-acryloyl- α,ω -diaminoalkane hydrochlorides, each repeat unit contributes one amide and one amine nitrogen species. Three signals are observed in the spectra, which we assigned as one amide and two amine salt signals. Where $n = 2$, (Fig. 2) the two amine salt signals are of approximately equal intensity and must represent terminal and branched units since, if the polymer was composed entirely of linear units, the terminal contributions would be negligible (only one signal per chain) and the linear salt signal would be equal in intensity to the amide signal.

In fact the sum of the relative intensities of the terminal and branched signals equals that of the amide signal within the limits of experimental error, an observation consistent with

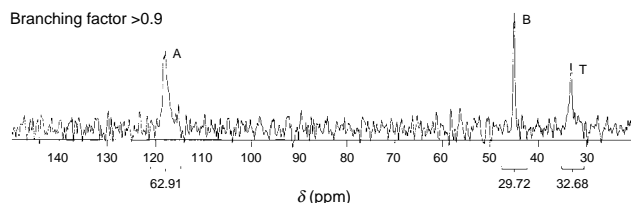


Fig. 2 Quantitative ^{15}N NMR spectrum (D_2O) of the polymer prepared from *N*-acryloyl-1,2-diaminoethane hydrochloride (pH 1)

virtually complete branching. For this system the relationship between the degree of branching⁷ and the terminal (T), branched (B) and amide (A) contributions can be expressed as: branching factor = $(B + T)/A$. It can therefore be concluded that the polymer is highly branched with few or no linear units, and within the limits of the experiment a degree of branching greater than 0.9 can be assigned. Only monomers with $n = 2$ give rise to such highly branched polymers. Increasing the internal CH_2 chain length of the monomer decreases the degree of branching; for example, the polymers where $n = 4$, display a branching factor of *ca.* 0.7, much closer to the statistical value proposed by Flory.⁴

These poly(amidoamine) hydrochlorides exhibit classic poly-electrolyte viscosity-concentration behaviour, which can be suppressed by the addition of 1% lithium chloride to allow an experimental value for intrinsic viscosity to be obtained. For these polymers we observe a trend of decreasing intrinsic viscosity with increasing molecular weight, a property more associated with dendritic than with linear structure.

As their hydrochloride salts these AB_2 poly(amidoamine) hyperbranched wedges are readily soluble in both water and MeOH, but are insoluble in all common organic solvents as their free bases. However, further work has revealed that core terminated systems, prepared through AB_2/B_n copolymerisations using the AB_2 monomer *N*-acryloyl-1,2-diaminoethane hydrochloride, retain their solubility as free bases. Consequently this work provides a simple route to hyperbranched polymers with a degree of branching approaching one and some of the structural features and properties of materials with perfect dendritic architecture.

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Footnote and References

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