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Hyperbranched Polymers by Thiol−Yne Chemistry: From Small Molecules to Functional Polymers

Dominik Konkolewicz,[†] Angus Gray-Weale,[‡] and Sébastien Perrier*[,†]

Key Centre for Polymers and Colloids, School of Chemistry, Building F11, University of Sydney,
NSW 2006, Australia, and School of Chemistry, Monash University, Victoria 3800, Australia

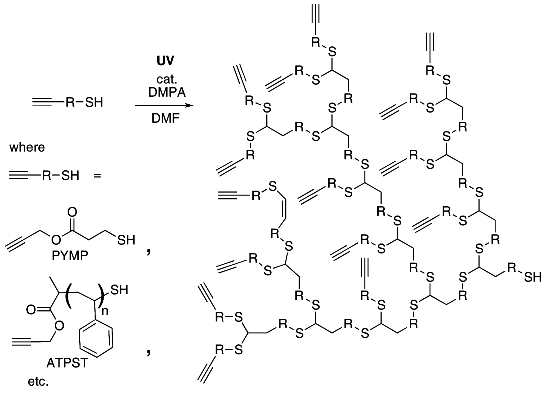
Received September 27, 2009; E-mail: s.perrier@chem.usyd.edu.au

Both hyperbranched polymers and dendrimers are highly branched polymers with physical properties that are vastly different from those of their linear analogues.[1−4] Highly branched polymers have potential applications such as drug-delivery vehicles, catalytic supports, and viscosity modifiers.[3,5−8] Dendrimers have regular treelike structures arranged into layers or generations. Their production requires the use of high-yield syntheses to ensure that each potential branch point is fully reacted. This makes dendrimers monodisperse macromolecules with very well defined architectures.[9−11] However, the precise structure comes at the price of complex syntheses that require multiple reaction and purification steps.[7,12−14] Hyperbranched polymers also have many branches, but these branches are distributed randomly throughout the polymer. Unlike the lengthy synthesis of dendrimers, hyperbranched polymers are easily prepared in a one-pot reaction,[5,15−17] which makes them attractive alternatives to dendrimers. This paper outlines a new synthesis of hyperbranched polymers that utilizes a thiol−yne reaction. The benefits of the thiol−yne approach are the versatility of the reaction in terms of reaction conditions (yields over 95% within 2 h at room temperature) and its tolerance of chemical functionality, to yield hyperbranched polymers from small molecules or macromolecules.

Recently, thiol chemistry has attracted significant interest in the polymer literature. In particular, the thiol−ene reaction has been proposed as a new "click" reaction.[18,19] Thiol−ene reactions have been used to synthesize polymers such as dendrimers and stars[14,20] as well as to add functionality to a macromolecule.[21] In contrast, the thiol−yne reaction has received much less interest.[22] The thiol−yne reaction involves addition of a thiol to an alkyne followed by addition of another thiol to the resulting alkene, giving a fully saturated species. Recently, this reaction has been used to synthesize network structures,[23] small molecules,[24] and dendrimers[25] as well as to attach small molecules to polymers.[26] In this work, we have synthesized molecules that have a thiol at one end of the molecule and an alkyne at the other. A molecule bearing a thiol and an alkyne is an AB_2 type monomer, where A reacts with either of the B components. In this case, the thiol is the A unit, and each π bond in the alkyne is a B unit. This work demonstrates for the first time that the thiol−yne reaction can be used to synthesize hyperbranched polymers from a wide variety of functional molecules bearing an alkyne and a thiol.

Scheme 1 depicts the hyperbranched polymer formed by the thiol−yne reaction. A photoinitiator [2,2-dimethoxy-2-phenylacetophenone (DMPA)] catalyzes the reaction. Hyperbranched polymers can be synthesized from small molecules [e.g., prop-2-ynyl 3-mercaptopropanoate (PYMP)] or macromolecules [e.g., alkyne-terminated polystyrene thiol (ATPST)]. A major benefit of this approach to synthesizing hyperbranched polymers is the ease with which a wide variety of functional groups can be incorporated into the polymer. Techniques such as reversible addition−fragmentation chain transfer (RAFT)[27] can be used to synthesize well-defined linear chains from a variety of functional monomers. The robustness of the thiol−yne reaction allows the facile formation of functional hyperbranched polymers from such linear chains.

Scheme 1. Polymerization of a Molecule Bearing an Alkyne and a Thiol To Give a Hyperbranched Polymer (This Paper Considers PYMP and ATPST)



To illustrate the formation of hyperbranched polymers by the thiol−yne reaction, PYMP was polymerized with 3 wt % DMPA under UV radiation at room temperature, taking samples at 10, 20, 40, and 90 min. The photopolymerization of PYMP was very fast, reaching nearly 70% conversion in 10 min and 99% in 90 min. The molecular weight distributions were broad, with many high-molecular-weight polymers, even after 10 min of UV irradiation. Figure 1 shows the evolution of the ^{1}H NMR spectrum at 10, 20, 40, and 90 min. We observe the decrease of the signal at 4.8 ppm, which is due to the ester linkage near the alkyne, and the appearance of a broad peak at 4.3 ppm, which corresponds to the ester linkage after full reaction of the alkyne to form a saturated bond. We also observe the broadening of other peaks such as that for the unreacted alkyne proton at 2.5 ppm. In each sample, we observe a negligible signal in the alkene region of the ^{1}H NMR spectrum (5−6.5 ppm) that cannot be quantified, thus suggesting that the addition of a sulfur radical to an alkyne is slow relative to the thiol−ene reaction, where a sulfur radical adds to the alkene formed by the first sulfur addition. The conversion was determined using ^{1}H NMR analysis. A molecule with an alkyne and a thiol has a 2-fold excess of π bonds relative to thiols. The rapid thiol−ene reaction implies that each molecule with a thiol and an alkyne at the start of the reaction has a 50% probability of being an unreacted alkyne in the final branched polymer. This implies that at any time, the alkyne group of a molecule is either unreacted or fully saturated. Early in the

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[†] University of Sydney.
[‡] Monash University.

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reaction, most of the alkynes are unreacted, while late in the reaction, the probability of an alkyne being fully saturated is 50%. The ratio of reacted to unreacted alkyne gives the conversion, as shown in the Supporting Information.

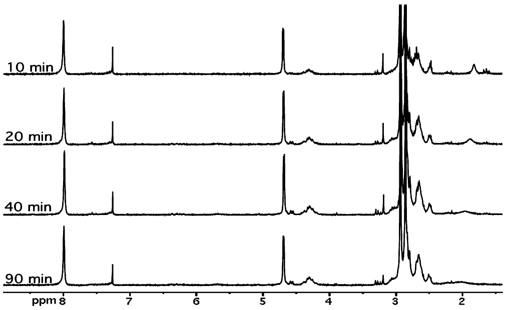

Figure 1. Evolution of the ^{1}H NMR spectrum for the photopolymerization of PYMP over time.

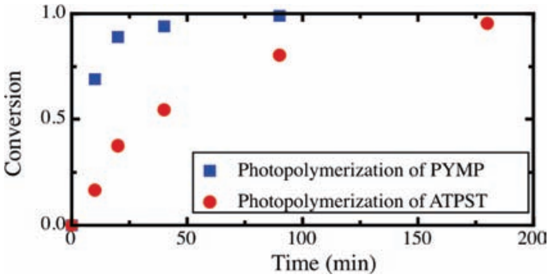

Figure 2. Conversion of PYMP and ATPST as a function of time.

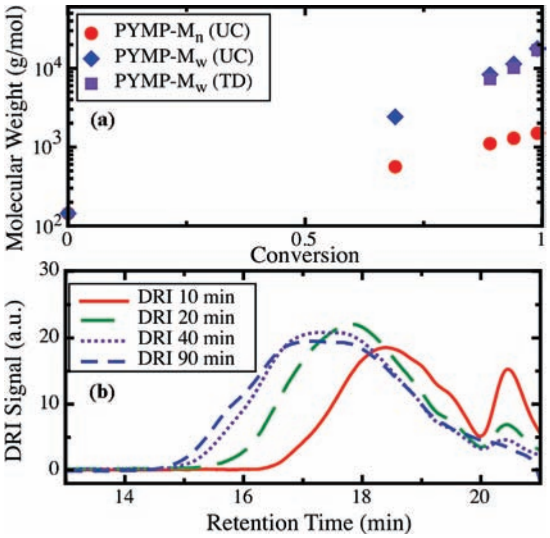

Figure 3. (a) Evolution of the number- and weight-averaged molecular weights with conversion for the photopolymerization of PYMP. (b) Time evolution of the DRI trace for the photopolymerization of PYMP.

Figure 2 shows the conversion of PYMP over time, while Figure 3a shows the evolution of both the number-averaged molecular weight (M_n) and the weight-averaged molecular weight (M_w) with conversion. M_n was calculated using universal calibration (UC), and M_w was calculated using both UC and triple detection (TD).[28] The only exception was the 10 min sample, where M_w was found by UC only, since there was no discernible peak in the light scattering (LS) data. Both M_n and M_w increase rapidly with conversion, with M_w growing faster than M_n, leading to a high dispersity index, as detailed in the Supporting Information. Figure 3b shows the evolution of the differential refractive index (DRI) trace for the photopolymerization of PYMP. The viscometric and LS responses are given in the Supporting Information. The DRI signal is proportional to the mass of polymer that elutes and therefore is indicative of the molecular weight distribution. As the reaction proceeds, the peak of the PYMP monomer at a retention time of 20.5 min decreases, and instead a new peak appears at higher molecular weight and shorter retention time. As the irradiation time is increased, the hyperbranched polymers become larger and have higher molecular weights. This is shown by the shift of the DRI trace in Figure 3b toward short retention times and higher molecular weights as the reaction proceeds.

PYMP is an excellent model system for hyperbranched polymers synthesized by the thiol−yne reaction, but hyperbranched polymers with tunable functionality are needed for many applications. Applying the thiol−yne reaction to linear polymers bearing an alkyne and a thiol allows the hyperbranched polymer to incorporate additional functionality. In this work, RAFT was used to synthesize the linear chains with alkyne and thiol functionalities as α- and *ω*-end groups. The RAFT agent (prop-2-ynyl propanoate)yl butyl trithiocarbonate (PYPBTC) was used to synthesize linear chains, since it has an alkyne moiety on the R group of the RAFT agent and the trithiocarbonate can be transformed into a thiol by aminolysis after polymerization.[29] PYPBTC was used to synthesize linear chains of polystyrene with a theoretical M_n of 707 g/mol. The M_n and M_w values for the linear polymer, as determined by size-exclusion chromatography (SEC) using UC, were 735 and 787 g/mol, respectively, giving a dispersity index of 1.07. The measured M_n was in excellent agreement with the theoretical value. The trithiocarbonate was removed by treating the RAFT polymer with 40 mol equiv of isopropylamine. The polymer's UV absorbance at 300 nm was measured before and after aminolysis. The Supporting Information shows that the UV absorbance was negligible after aminolysis, confirming the transformation of the trithiocarbonate to a thiol and the formation of ATPST. Figure 4b shows the DRI trace of the RAFT-synthesized polymer before aminolysis (DRI RAFT) and after aminolysis (DRI SH-Lin). These traces are almost identical, which shows that minimal thiol−thiol coupling occurred after aminolysis.

ATPST was photopolymerized with 5 wt % DMPA and proceeded to 95% conversion after 180 min. Figure 2 shows the conversion of ATPST over time and compares it with that of PYMP. The photopolymerization is slower for ATPST than PYMP because the polymer chain in ATPST lowers the concentration of thiols and alkynes. A detailed NMR analysis is given in the Supporting Information. Figure 4a plots M_n and M_w against conversion. Both M_n and M_w increase rapidly with conversion, similar to the reaction of PYMP. M_w grows faster than M_n, causing a high dispersity index, as shown in the Supporting Information. Figure 4b shows the evolution of the DRI trace over time, with the viscometric and LS responses in the Supporting Information. The DRI trace shows the consumption of the linear polymer and formation of high-molecular-weight species as the reaction proceeds.

Hyperbranched polymers formed by thiol−yne reactions have degrees of branching (DB) almost as high as those of dendrimers. In a dendrimer, there are no semireacted sites; hence, each unit is either terminal or fully branched (dendritic), and DB = 1. In a hyperbranched polymer made from a thiol−yne monomer, alkynes are terminal groups, alkenes are the result of one addition to the alkyne, and fully saturated species are the dendritic units. The NMR data show that no quantifiable amount of alkene is present at any point in time, and hence, there are very few "linear" or semireacted groups in the hyperbranched polymer. This implies that the DB of

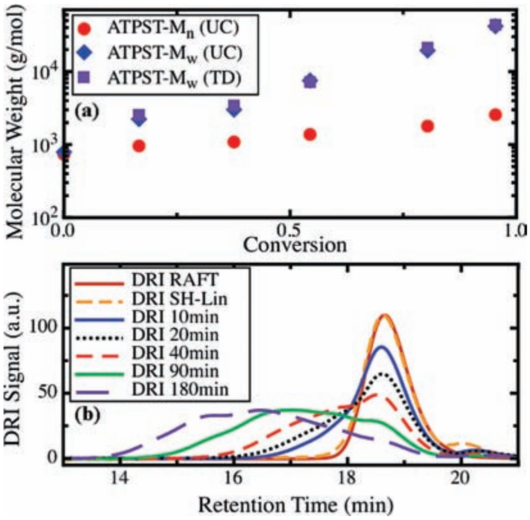

Figure 4. (a) Evolution of number- and weight-averaged molecular weights with conversion for the photopolymerization of ATPST. (b) Time evolution of the DRI trace for the photopolymerization of ATPST.

a hyperbranched polymer made by the thiol−yne reaction should be very high, with a value close to 1. This is much higher than for conventional AB_2 polymerization, which gives DB = 0.5.[8] However, the branches in a polymer made by the thiol−yne method have unequal lengths. Additionally, hyperbranched polymers prepared by the thiol−yne reaction have many π bonds in their structure. Residual π bonds are due to the 2:1 ratio of π bonds to thiols, with the excess π bonds almost always being alkynes. Hence, each end group in the polymer except one is an alkyne, which can serve as a potential handle for further functionalization (e.g., by azide−alkyne "click" chemistry).

Hyperbranched polymers made by the thiol−yne reaction have many unique features. The thiol−yne reaction occurs at room temperature and is very rapid compared with other reaction methods.[8] Since the thiol−yne reaction uses a radical mechanism to transform (macro)molecules into hyperbranched polymers, the tolerance to functionality should be similar to that for self-condensing vinyl polymerization.[1] Since the data show minimal amounts of alkene, the thiol−yne reactions must give high DBs, much larger than the value of 0.5 for conventional AB_2 polymerization.[8] Moreover, the effective DB can be easily controlled simply by changing the length of the linear chain between the thiol and the alkyne.

We have demonstrated a versatile approach to the synthesis of functional hyperbranched polymers. The thiol−yne reaction occurs at room temperature, reaches yields over 95% in less than 2 h, and enables the incorporation of various functionalities in the final product. The reaction applies to both small molecules and linear chains with a thiol and an alkyne. Techniques such as RAFT can be used to synthesize a large library of such linear chains, which can be converted into hyperbranched polymers following the strategy outlined in this paper. We believe the simplicity and versatility of this approach makes the thiol−yne reaction an ideal candidate for the synthesis of hyperbranched polymers.

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Supporting Information Available: Experimental methods, ^{1}H and ^{13}C NMR and MS data for PYMP, ^{1}H NMR data for PYPBTC, UV data for polystyrene before and after aminolysis, viscometric and LS SEC data for the photoreaction of PYMP and ATPST, and NMR data for ATPST. This material is available free of charge via the Internet at http://pubs.acs.org.

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