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Synthesis of Cyclic Polystyrenes Using Living Anionic Polymerization and Metathesis Ring-Closure

Roderic P. Quirk,* Shih-Fan Wang, and Mark D. Foster

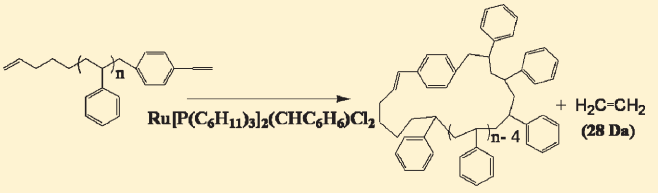
Institute of Polymer Science and Polymer Engineering, The University of Akron, Akron, Ohio 44325-3909, United States

Chrys Wesdemiotis and Aleer M. Yol

Department of Chemistry, The University of Akron, Akron, Ohio 44325-3601, United States

Supporting Information

ABSTRACT: A combination of living anionic polymerization and metathesis ring-closure provides an efficient method for synthesis of well-defined, macrocyclic polymers over a broad molecular weight range. A series of well-defined, α,ω-divinylpolystyrene precursors (M_n = 2800, 8600, 17000, and 38000 g/mol) were synthesized by 4-pentenyllithium-initiated polymerization of styrene followed by termination with 4-chloromethylstyrene. Efficient cyclization of these α,ω-divinylpolystyrene precursors was effected in CH_2Cl_2 and CH_2Cl_2/cyclohexane mixtures using a Grubb's catalyst, bis(tricyclohexylphosphine)benzylidine ruthenium(IV) chloride. As the precursor M_n increased, more cyclohexane was added and the concentration of the precursor was decreased from 1.41×10^{-4} to 2.15×10^{-6} M. The macrocyclic polymers were uniquely characterized by MALDI−TOF mass spectrometry in terms of peaks that appeared characteristically 28 m/z units lower than those of the corresponding open-chain precursor peaks, corresponding to the loss of an ethylene unit. Relative to linear analogues, the macrocycles exhibited longer SEC retention volumes, lower intrinsic viscosities, and higher T_gs at the lower M_n values.



INTRODUCTION

The synthesis and characterization of macrocyclic polymers have presented fascinating challenges and rewards for polymer chemists and theoreticians.[1−9] Macrocyclic polymers are of intrinsic interest because of their unusual architecture (topology), i.e., their lack of end groups and the consequences of their reduced hydrodynamic volumes. For example, macrocyclic polymers exhibit lower solution viscosities, higher SEC elution volumes, lower mean square radii of gyration, higher glass transition temperatures (X_n < 400), lower theta (Θ) temperatures,[1,6,9] higher melt densities,[10] lower zero shear viscosities,[11] faster relaxation times, absence of an entanglement plateau, and faster diffusion coefficients[12] compared to their linear analogues. Of particular interest with respect to our ongoing research on the preferential surface segregation of topologically diverse macromolecules[13] is the prediction of Wu and Fredrickson[14] that in a melt blend with linear polymers the ring polymers will be preferentially enriched at the surface at twice the bulk concentration.

Major advances in structure−property investigations have been limited by the fact that efficient syntheses of well-defined macrocylic polymers with a broad range of molecular weights present significant challenges. Among the most common methods of synthesis of macrocyclic polymers are end-to-end linking reactions, which are generally limited by competing chain-extension reactions that are more likely to occur with increasing chain length.[1−7,9] Increasing the size reduces the probability of two chain ends interacting intramolecularly, with an inverse $^5/_2$ power dependence on molecular weight, as first described by Jacobson and Stockmayer.[15] Several groups have developed relationships showing a negative $^3/_2$ power dependence on molecular weight for the intramolecular cyclization of α,ω-dianions with difunctional electrophiles.[16,17] It is also noteworthy that first-order cyclization reactions are obviously favored over the second-order chain-extension reactions by high dilution.[6,16]

Tremendous advances in the controlled synthesis of macrocyclic polymers have followed the development of a variety of new living polymerization systems; however, extensive fractionation to remove higher molecular weight components has generally been required for these systems.[5,6] Recently, several groups have reported new, efficient syntheses of macrocyclic polymers by end-to-end cyclization reactions with well-defined, telechelic (α,ω-difunctional) precursors.[1,3,18,19] One of these exciting developments has been the application of "click" reactions, which are very efficient, simple reactions.[20] Thus, Laurent and Grayson[21] initiated the atom-transfer radical polymerization (ATRP) of styrene with propargyl 2-bromoisobutyrate and cuprous bromide; the resulting α-propargyl-ω-bromopolystyrene was converted

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to the corresponding α-propargyl-ω-azidopolystyrene with sodium azide. An intramolecular "click" cyclization was effected by slow addition (25 h) of a very dilute solution of this telechelic polystyrene (0.01 mmol in 5 mL) to a DMF solution containing Cu(I)Br and dipyridine. They reported nearly quantitative syntheses of the corresponding macrocyclic polystyrenes (M_n = 2200 and 4200 g/mol) using this technique, albeit in small quantities; the polydispersity (M_w/M_n) of the precursor was described as <1.2. Hoskins and Grayson[22] prepared narrow polydispersity [M_w/M_n(SEC) = 1.07−1.20] cyclic polycaprolactones (M_n = 2100−13800 g/mol) by click cyclization of α-azido-ω-alkynylpolycaprolactone. Optimization of the "click" approach to complete cyclization reactions in minutes at more convenient reaction conditions was reported by Lonsdale et al.[23] The click methodology was recently extended to the preparation of cyclic poly(methyl acrylate-*block*-styrene).[24] Analogously, Tezuka and co-workers[25] have prepared an α,ω-divinylpoly(methyl acrylate) by ATRP using a difunctional initiator (dimethyl 2,6-dibromoheptanedioate) and cuprous bromide followed by termination with allyltributyltin. Efficient ring-closure of this α,ω-diallyl telechelic polymer was effected under dilute conditions in the presence of Grubbs' first generation catalyst; the polydispersity was 1.58 for the precursor and 1.51 for the macrocycle. Binder and co-workers[26] have synthesized macrocyclic polyisobutylenes using either ring-closing metathesis or click chemistry; the reported M_w/M_n values were 1.25. Grubbs and co-workers[27,28] have developed a very efficient cyclic metathesis catalyst that polymerizes cyclic dienes such as 1,5-cyclooctadiene to macrocyclic polybutadienes; however, the kinetic chain length is limited by intramolecular chain transfer. Thus, the resulting polymers exhibited random molecular weight distributions, i.e., polydispersity = 2. A novel approach for synthesis of polymeric macrocycles, developed by Tezuka et al.,[19,29] is based on electrostatic self-assembly of polymeric precursors having reactive, five-membered cyclic ammonium salt groups with dicarboxylates followed by covalent fixation by nucleophilic ring-opening by the carboxylate groups. For example, a well-defined, α,ω-di(*N*-phenylpyrrolidinium)polytetrahydrofuran ditriflate, prepared by living cationic polymerization initiated with trifluoromethanesulfonic anhydride and terminated with *N*-phenylpyrrolidine, was reacted with a small molecule dicarboxylate (disodium 4,4′-biphenyldicarboxylate) and the product precipitated from solution as a result of electrostatic self-assembly. The corresponding polymeric macrocycle was obtained in 91% yield (71% isolated) by heating a dilute solution of the salt complex. These methodologies as well as other recent advances have been the subject of several recent reviews.[1,3,7,18,19]

Alkyllithium-initiated anionic polymerization is one of the most reliable methods for the synthesis of well-defined, chain-end functionalized polymers with controlled molecular weights, narrow molecular weight distributions, and high end-group functionality.[30] Therefore, it was of interest to investigate the use of living anionic polymerization to prepare well-defined, narrow molecular weight distribution α,ω-divinylpolystyrenes coupled with an efficient ring-closure methodology, i.e., metathesis ring-closure, for the efficient synthesis of well-defined, macrocyclic polymers. It was envisioned that the ability to unambiguously characterize the macrocycle relative to the precursor by MALDI−TOF mass spectrometry via the loss of 28 m/z units would be of intrinsic value. A test of the efficiency of this methodology over a broad molecular weight range (M_n = 2800−38000 g/mol) is reported herein.

EXPERIMENTAL SECTION

Materials. Benzene (Certified ACS, EM Science), styrene (99%, Aldrich), and tetrahydrofuran, (THF), (Fisher Scientific, >95%)) were purified as previously reported.[31] 5-Bromo-1-pentene (95%, Aldrich) was fractionally distilled in vacuum, stirred over calcium hydride, and then distilled into a calibrated, flame-sealed ampule. 4-Vinylbenzyl chloride (Aldrich, >90%) was dried over calcium hydride, vacuum-distilled into a sealed flask, distributed into ampules in a drybox, and the ampules were flame-sealed on the vacuum line. Lithium metal (stabilized, 1% Na, FMC) was used without further purification. Benzene (EMD, 99%) and heptane (EMD, 99%) were distilled from poly(styryl)lithium as needed. Diethyl ether (EMD, 99%) and tetrahydrofuran were distilled from a sodium mirror as needed. Methanol (Fisher Scientific, reagent grade) was degassed on the vacuum line before distilling into ampules followed by flame-sealing.

Synthesis of 5-litho-1-pentene.[32] A 250 mL, Morton-creased, glass reactor equipped with ampules of diethyl ether (20 mL), 5-bromo-1-pentene (6.5 mL, 0.0549 mol), lithium metal (3.81 g, 0.549 mol; 10-fold excess), and with a fritted glass filter connected to an empty ampule and a stir bar was placed under high vacuum. Heptane was distilled into the reactor and the reactor was separated from the vacuum line by flame sealing. The break-seals of the lithium metal and 5-bromopentene ampules were broken sequentially and the reaction was stirred at room temperature for 3 days. The reactor and diethyl ether ampule were cooled to 0 °C and the ampule break-seal was broken. The reaction was stirred for 24 h at 0 °C. The reactor was then connected to the vacuum line via a break-seal, solvent was removed by flash distillation and 50 mL of heptane was added by distillation. The mixture was transferred through the glass filter into the empty ampule that was then flame-sealed from the reactor. The product was 0.60 M 5-lithio-1-pentene (53.6%) as determined by double titration.[33]

Synthesis of α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene (M_n = 2800 g/mol). All polymerizations were carried out in all-glass apparatus using standard high vacuum techniques.[34] 5-Lithio-1-pentene (5.80 mL, 1.74 mmol, 0.3 M) was added to the A part of an all-glass reactor which consisted of two, connected reaction flasks. Reactor A was equipped with a styrene ampule (4.75 mL, 4.32 g, and 0.0415 mol), a tetrahydrofuran ampule (1.41 mL, 1.25 g, 17.4 mmol), a sampling flask with an attached methanol (~2 mL) ampule, and the other flask (B) was equipped with an ampule containing 4-vinylbenzyl chloride (2.45 mL, 2.66 g, 17.4 mmol)/ THF (90 mL). Benzene (50 mL) was distilled into the reactor after flame-sealing the reactor to the vacuum line and evacuation. The reactor was then separated from the vacuum line by flame sealing and the break-seals of the THF and styrene ampules were broken sequentially. The reactor was placed in a water bath at 0 °C for 3 h. After reattaching the reactor to the vacuum line via a break-seal, the solvent was removed by flash distillation and replaced by THF (100 mL). This base polymer sample was separated, flame-sealed from the reactor and quenched with methanol. The polymer sample was precipitated into methanol and characterized by SEC, ^{1}H NMR, and MALDI−TOF mass spectrometry.

All glassware was cooled to −78 °C and α-4-pentenylpoly(styryl)-lithium in flask A was slowly transferred into the vinyl benzyl chloride/THF solution in flask B. The color changed from orange to yellow. After the α-4-pentenylpoly(styryl)lithium solution was completely transferred, THF was removed by distillation under reduced pressure. The resulting white powder was dissolved in benzene, precipitated into methanol (10 times solution volume), washed with methanol several times, freeze-dried from benzene and characterized by ^{1}H NMR, ^{13}C NMR, SEC, and MALDI−TOF mass spectrometry.

Synthesis of Macrocyclic Polystyrene (M_n = 2700 g/mol). In a recirculating, argon-atmosphere drybox, α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene (0.2 g, 0.0714 mmol; M_n = 2800 g/mol) in

dichloromethane (15 mL) was sealed in an ampule and bis-(tricyclohexylphosphine) benzylidine ruthenium(IV) chloride (0.141 g, 0.171 mmol) in dichloromethane (15 mL) was sealed in another ampule. The all-glass reactor equipped with the two ampules was connected to the vacuum line by flame sealing and placed under high vacuum. After distillation of dichloromethane (475 mL) into the reactor and flame-sealing it off from the vacuum line, α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene and ruthenium catalyst were added sequentially by smashing their respective break-seals. After heating under reflux for 24 h at 40 °C, the reactor was reconnected to the vacuum line and the solvent was removed by flash distillation. The residual catalyst was removed by silica gel column chromatography using toluene as eluent. The polymer product was isolated by precipitation of the solution into methanol and then freeze-drying from benzene. The polymer was characterized by ^{1}H NMR, ^{13}C NMR, SEC, and MALDI−TOF mass spectroscopy.

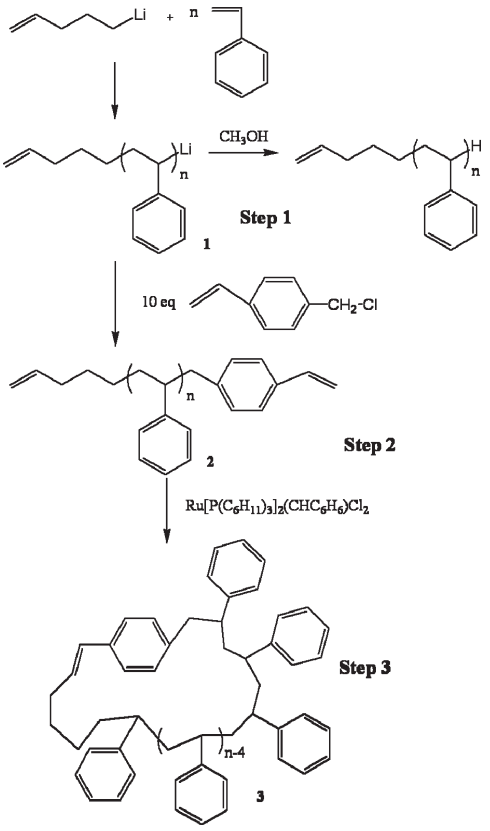
Characterization. Size exclusion chromatographic analyses (SEC) for the polymers were performed using a Waters 150-C Plus instrument equipped with three HR-Styragel columns [100 Å, mixed bed (50/500/10^3/10^4 Å), mixed bed (10^3, 10^4, 10^6 Å)] and a triple detector system. The three detectors included a differential refractometer (Waters 410), a differential viscometer (Viscotek 100) and a laser light scattering detector (Wyatt Technology, DAWN EOS, λ = 670 nm). THF was used as eluent with a flow rate of 1.0 mL/min at 30 °C. Samples were prepared in tetrahydrofuran (10 mg/mL) and passed through a 0.45 μm Teflon filter before analysis. Results were analyzed using Wyatt ASTRA software (version 4.73.04, Viscoteck Corp). The intrinsic viscosity analyses were performed using the Viscotek viscometer described above and the results were analyzed using Omni SEC software (Version 4.3.1.246). The fraction of higher molecular weight product (e.g., dimer) in the SEC chromatograms of polymers was estimated by Gaussian curve resolution using OriginPro 7.5 software.

^{1}H NMR and ^{13}C NMR spectra were obtained on a Varian 500 spectrophotometer (500 MHz) using 20 mg of polymer dissolved in 1 mL of $CDCl_3$ (Cambridge Isotopes). MALDI−TOF/TOF mass spectra were recorded on a Bruker Ultraflex-III MALDI−TOF/TOF mass spectrometer (Bruker Daltonics, Billerica, MA equipped with a Nd: YAG laser (355 nm). Solutions of DCTB {2-[(2E)-3-(4-*tert*-butylphenyl)-2-methylprop-2-enylidene]malononitrile} (20 mg/mL) (Alfa Aesar, 99+%), polymer sample (10 mg/mL), and silver trifluoroacetate (10 mg/mL) (Aldrich, 98%) were prepared in THF (Aldrich, 99.9%). These solutions were mixed in the ratio of matrix:cationizing salt:polymer (10:1:2), and 0.5−1.0 μL of the mixture was applied to the MALDI sample target and allowed to dry. In order to minimize polymer fragmentation, the intensities of the laser pulses were frequently attenuated and adjusted to obtain the optimal signal intensity. Mass spectra were measured in the positive reflectron and linear modes. The mass scale was calibrated externally using the peaks of a polystyrene standard at the molecular weight under consideration for the determination of molar masses (see Supporting Information: Experimental Section S-A describes the external calibration method for MALDI−TOF MS including the data in Tables S1 and S4). Glass transition temperatures of macrocyclic polystyrenes were measured with a TA Instruments Q10 differential scanning calorimeter (DSC) equipped with the RCS cooling system. The heating scans were performed from −20 to +150 °C at a heating rate of 10 °C/min. Thermal transitions were analyzed using the second heating scans.

RESULTS AND DISCUSSION

The first goal of this research was to develop a general method for the synthesis of well-defined, α,ω-divinylpolystyrenes that could then undergo intramolecular cyclization using a metathesis catalyst (see Scheme 1).

Scheme 1. Reaction Pathway for the Synthesis of Macrocyclic Polystyrenes



Living alkyllithium-initiated polymerization of styrene is one of the most reliable methods for the synthesis of polystyrenes with controlled, predictable molecular weights, narrow molecular weight distributions and the potential for high-yield, chain-end functionalizations.[30] It was envisioned that one of the best ways to accomplish the desired goal was to use an unsaturated, i.e. vinyl-substituted, alkyllithium initiator in hydrocarbon solution. A living polymerization with a functional initiator ensures that every chain will have the functional group at the initiating, α, chain-end.[35] For this purpose, the initiator 5-lithio-1-pentene was prepared.

Preparation of α-(4-pentenyl)poly(styryl)lithium. 5-Lithio-1-pentene was prepared using the procedure described by Takano and co-workers[32] from the reaction of lithium metal with 5-bromo-1-pentene in heptanes. This initiator was used to polymerize styrene in benzene with ten equivalents of THF. THF was added to this primary alkyllithium initiator to increase the rate of initiation relative to rate of propagation in order to obtain a narrow molecular weight distribution product.[30,36,37] An aliquot of the resulting α-4-pentenylpoly(styryl)lithium was quenched with methanol. All SEC (Figure S1), NMR spectroscopic (Table S7 and Figure S3) and MALDI−TOF MS (Figure S2) characterization results (see Supporting Information Section S-B) are consistent with the formation of α-4-pentenylpolystyrene in high yield, with controlled molecular weight and narrow molecular weight distribution using 5-lithio-1-pentene as initiator in the presence of THF. Several different α-4-pentenylpolystyrenes with different molecular weights were prepared and their characterization data are listed in Table 1.

Table 1. Molecular Characterization of α-(4-Pentenyl) Polystyrenes (Base Polymer) and α-4-Pentenyl-ω-(p-vinylbenzyl)polystyrene (Precursor)

	base polymer		divinyl precursor		
polymer	M_n[a](g/mol)	M_w/M_n[a]	M_n[a] (g/mol)	M_w/M_n[a]	intrinsic viscosity $[\eta]_1$[b]
2k	2600	1.03	2800	1.09	0.07
7k	8200	1.10	8600	1.19	0.11
17k	16000	1.06	17000	1.10	0.15
37k	37000	1.03	38000	1.03	0.25

[a] Determined by SEC coupled with light scattering (±5%) in THF at 30 °C. [b] Determined by SEC coupled with viscometer (±10%) in THF at 30 °C (±0.5 °C).

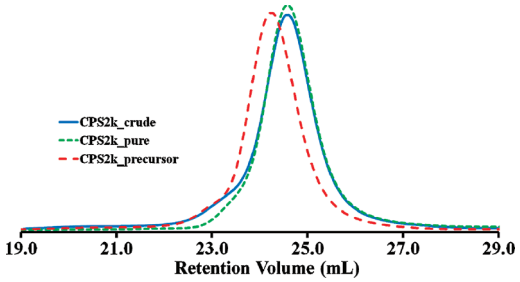


Figure 1. SEC chromatograms of α-4-pentenyl-ω-(p-vinylbenzyl)-polystyrene, the crude and fractionated macrocyclic polystyrenes.

Synthesis of α-4-Pentenyl-ω-(p-vinylbenzyl)polystyrene. The α,ω-dienyl-functionalized polystyrene, α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene, was prepared by slow, inverse addition of an α-4-pentenylpoly(styryl)lithium/THF solution (cooled to −78 °C) to a 10-fold excess of p-vinylbenzyl chloride in THF at −78 °C following the procedure of Asami and co-workers[38] for the synthesis of styrene-functionalized macromonomers.

The SEC chromatogram of α-4-pentenyl-ω-(p-vinylbenzyl)-polystyrene in Figure 1 shows a small shoulder (ca. 8 wt %) at smaller elution volume. Since this presumed dimer peak was not observed for the α-4-pentenylpolystyrene precursor (see Figure S1, Supporting Information), the formation of this side-product is ascribed to competing lithium-halogen exchange between α-4-pentenylpoly(styryl)lithium and p-vinylbenzyl chloride resulting in formation of an α-4-pentenyl-ω-chloropolystyrene intermediate that can undergo Wurtz coupling with α-4-pentenyl-poly-(styryl)lithium to form the corresponding dimer as characterized previously.[39] The SEC analysis for the total product corresponds to M_n = 2800 g/mol with M_w/M_n = 1.09.

The ^{1}H NMR spectrum (Figure 2a) of the expected product, α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene, exhibits one new terminal vinyl resonance at δ 5.2 ppm, characteristic of the formation of the ω-p-vinylbenzyl chain end (=CH_dH). The other expected terminal vinyl resonance (=CH$\underline{H}_{d'}$) at δ 5.7 ppm overlaps with the corresponding vinyl resonance from the α-pentenyl group (see Figure S3(a), Supporting Information) and the area of this peak is obviously larger compared to the corresponding peak in the Supporting Information, Figure S3(a); the other characteristic vinyl resonance (−CH=) from the 5-pentenyl group is clearly observed at δ 4.9 ppm (H_a). The expected internal vinyl proton resonance (−CH=, H_c) at ca. δ 6.4 ppm

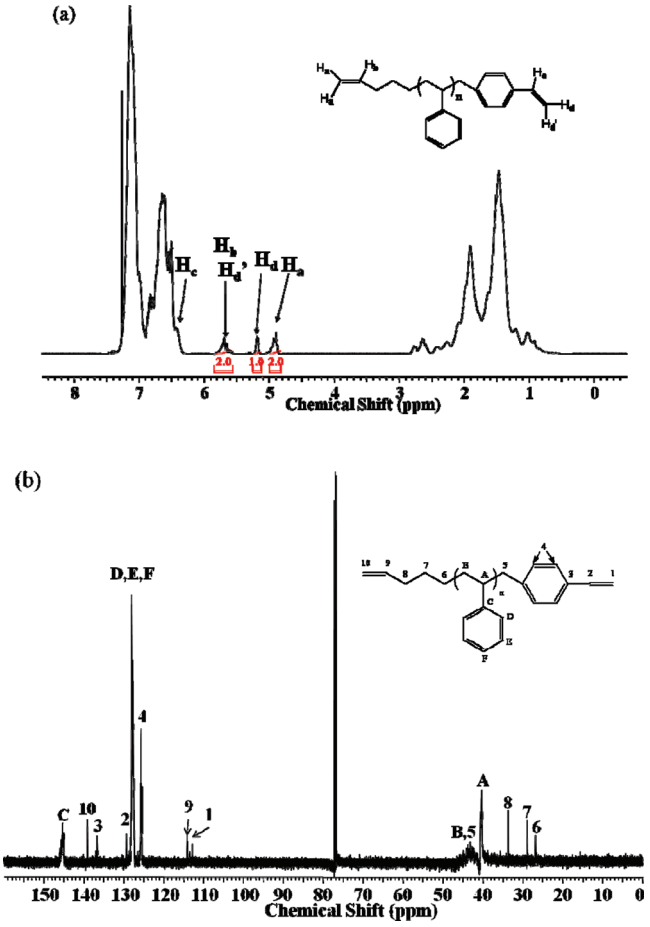


Figure 2. (a) ^{1}H NMR and (b) ^{13}C NMR spectra of α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene.

is superimposed with the aromatic proton resonances. Thus, the ^{1}H NMR spectral analysis is consistent with the formation of α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene.

The ^{13}C NMR spectrum of α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene is shown in Figure 2(b). The structural assignments shown in Table S7 (Supporting Information) are based on the application of the method of Grant and Paul[40] as described by Wehrli, Marchand, and Wehrli[41] and on the use of ChemNMR ^{13}C Estimation software. The observed ^{13}C NMR chemical shifts are in good agreement with those calculated based on the structure of α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene.

The MALDI−TOF mass spectrum of α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene is shown in Figure 3. There is one major distribution with a representative peak at m/z 2166.3 that corresponds to the 18-mer of α-4-pentenyl-ω-(p-vinylbenzyl)-polystyrene, $C_5H_9-(C_8H_8)_{18}-C_9H_9\cdot Ag^+$; the calculated monoisotopic mass [69.0704(C_5H_9) + 18 × 104.0626 (C_8H_8) +117.0704(C_9H_9) + 106.9051 (Ag^+)] = 2166.17 Da. There is a barely detectable, low intensity distribution that corresponds to monofunctional α-4-pentenylpolystyrene [$C_5H_9-(C_8H_8)_{20}-H\cdot Ag^+$] (representative peak at m/z 2258 for 20-mer), that presumably results from deactivation of the living chains by the solvent used, THF. The lack of MALDI−TOF MS peaks corresponding to the dimer fraction, observed by SEC, is attributed to the mass fractionation that occurs during the ionization process. Thus, SEC, ^{1}H and ^{13}C NMR, and the

MALDI−TOF mass spectral characterizations are in accord with the efficient synthesis of α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene with controlled molecular weight, narrow molecular weight distribution and high α,ω-vinyl chain-end functionality.

Macrocyclic Polystyrene. The ring-closure reaction of α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene (M_n = 2800 g/mol) at high dilution (1.41×10^{-4} M) was effected using bis(tricyclohexylphosphine)benzylidine ruthenium(IV) chloride (Grubb's first generation catalyst; 3.38×10^{-4} M) in dichloromethane under reflux in an all-glass, sealed reactor using standard high vacuum techniques.[34] The SEC chromatogram of the main product (see Figure 1) exhibited a symmetric, monomodal distribution (M_n = 2700 g/mol and PDI = 1.08) with the same small dimer shoulder (ca. 5%) as observed for the precursor (see Figure 1); the elution volume was larger than that of the starting polymer, α-4-pentenyl-ω-(*p*-vinyl-benzyl)polystyrene (see Figure 1). In general, the SEC retention volume of a macrocycle is larger compared to that of the linear precursor in accord with the systematic investigations of Roovers and Toporowskii.[42] After fractionation, the dimer peak was completely removed and the molecular weight distribution was 1.03 (see Figure 1). The ratio of the intrinsic viscosity of purified, macrocylic polymer to that of the linear precursor ($[\eta]_c/[\eta]_l$) was 0.60 (see Table 2), which is comparable with literature values for macrocycles (0.58−0.68),[6,42] and as expected for the more compact nature of the macrocycle compared to the linear precursor. Roovers[6] has noted that values higher than 0.70 should be considered as indicative of considerable contamination with linear material.

The ^{1}H NMR spectrum of the purified, macrocylic polystyrene is shown in Figure 4(a). The precursor, α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrene, has a vinyl group at each chain end. Comparison of ^{1}H NMR spectra for the linear precursor [Figure 2(a)] and macrocyclic polymer [Figure 4(a)] shows that the signals for the terminal vinyl protons at δ 4.9, 5.7 (initiator vinyl) and 5.7, 6.4 ppm (*p*-vinylbenzyl) disappeared; new internal vinyl protons at δ 6.0 and 6.2 ppm are observed as expected for the structure of the macrocycle (**3**) formed from the metathesis ring-closure reaction of **2** (see Scheme 1). The integration ratio of these two hydrogens is 1 to 1. The ^{13}C NMR spectrum of the macrocyclic polymer is shown in Figure 4(b). The most important observation from this spectrum compared to that of the α,ω-divinyl precursor, **2**, is that the terminal vinyl groups are lost, and the remaining signals are obscured (carbons 1, 2, 9, 10; see Table S7 (Supporting

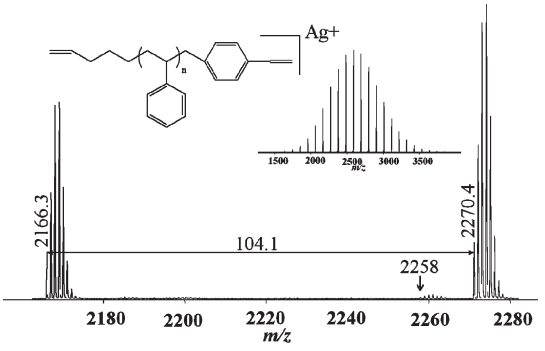


Figure 3. MALDI−TOF mass spectrum of 2k α-4-pentenyl-ω-(*p*-vinylbenzyl) polystyrene.

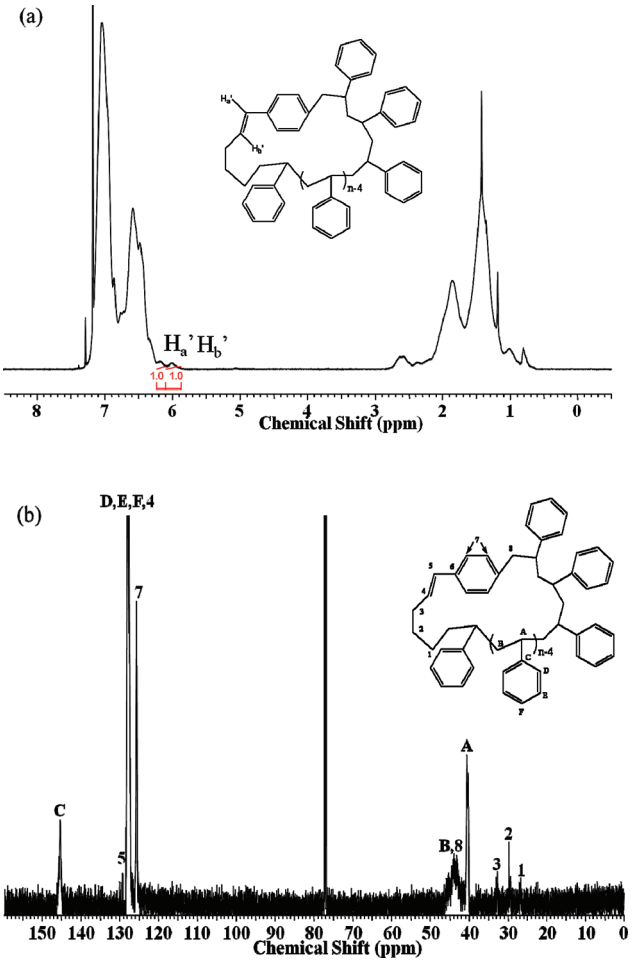


Figure 4. (a) ^{1}H NMR and (b) ^{13}C NMR spectra of 2k purified macrocylic polystyrene.

Table 2. Molecular Characterization of Macrocylic Polystyrenes

	macrocylic polymer					
polymer	M_n[a] (g/mol)	M_w/M_n[a,b]	intrinsic viscosity $[\eta]_c$[c]	$[\eta]_c/[\eta]_l$[c]	$T_{g,l}$ (°C)[d]	$T_{g,c}$ (°C)[d]
2k	2700	1.08 (1.03)[b]	0.042	0.60	59.4	85.4
7k	7100	1.12 (1.01)[b]	0.064	0.61	89.7	97.2
17k	13 000	1.18 (1.02)[b]	0.088	0.58	98.9	99.5
37k	37 000	1.09 (1.03)[b]	0.20	0.77	104.0	104.0

[a] Determined by SEC coupled with light scattering (±5%) in THF at 30 °C. [b] M_w/M_n in the parentheses is for the purified sample. [c] Determined by SEC coupled with viscometer (±10%) in THF at 30 °C (±0.5). [d] Measured at a heating rate of 10 °C/min using DSC (±1 °C) and collected from the second heating scans.

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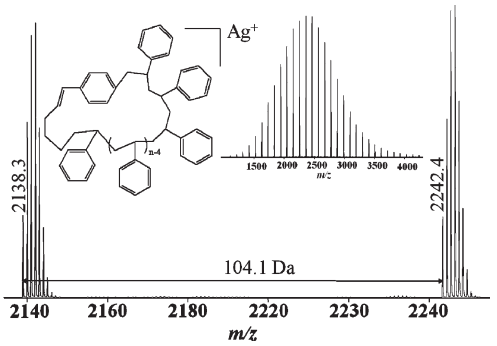

Figure 5. MALDI−TOF mass spectrum of crude 2k macrocyclic polystyrene.

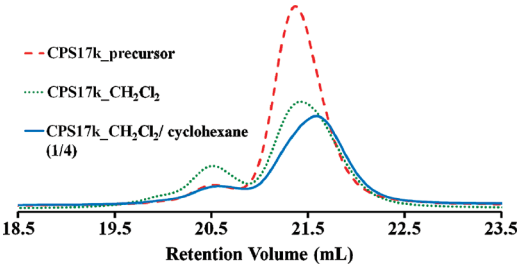

Figure 6. SEC chromatograms of the 17k divinyl precursor and the macrocyclic polystyrenes prepared in CH_2Cl_2 and in CH_2Cl_2/cyclohexane.

Information) for chemical shifts). The predicted ^{13}C chemical shifts for the vinyl carbons in the macrocycle are δ 129.6 and 126.9 ppm; however, these peaks appear to overlap with other carbon resonances.

MALDI−TOF mass spectrometry has proven to be the most definitive characterization method to confirm the macrocyclic structure for the metathesis ring-closure products from the α,ω-divinylpolystyrenes. The spectrum of the crude macrocyclic polymer (Figure 5) shows a monomodal distribution. A representative monoisotopic peak at m/z 2138.3 corresponds to the 18-mer of the macrocyclic polystyrene, $[C_{12}H_{14}\text{-}(C_8H_8)_{18}\cdot Ag^+]$; the calculated monoisotopic mass [158.1095 ($C_{12}H_{14}$) + 18 × 104.0626 (C_8H_8) + 106.9051 (Ag^+)] is equal to 2138.14 Da. Furthermore, since the macrocyclic product was produced by the elimination of an ethylene molecule from the divinyl precursor, the difference in molar mass (and m/z value) between a given monoisotopic peak from the macrocyclic polymer and the corresponding peak from the linear precursor would be expected to be 28.0 units. Indeed, the monoisotopic peak of the 18-mer macrocyclic polystyrene is observed at m/z 2138.3 (see Figure 5), while the monoisotopic peak for the corresponding linear 18-mer precursor is observed at m/z 2166.3 (see Figure 3), i.e. the expected difference of m/z 28 is observed. Thus, the MALDI−TOF mass spectral results are in excellent agreement with the assignment of a macrocyclic structure to the product. The SEC chromatograms, NMR spectra and MALDI−TOF mass spectra of the crude product from the cyclization reaction provide direct evidence of the efficiency of this ring closure reaction to produce a well-defined macrocycle with a narrow molecular weight distribution.

Macrocyclization of Higher Molecular Weight Precursors. It is well-known that the efficiency of ring-closure reactions for macrocycle formation decreases with increasing chain length, as predicted by the theoretical treatment of Jacobson and Stockmayer[15] showing that the probability of two chain ends coming together varies as the inverse $^5/_2$ power of the degree of polymerization. Therefore, it was of interest to determine if this metathesis ring-closure procedure for macrocycle synthesis is effective for higher molecular weight (i.e., longer chain) precursors of the relatively stiff polystyrene. It is noteworthy that other recent reports of efficient ring-closing polystyrene macrocycle syntheses have been limited to M_n = 10 000 g/mol (350 atoms in a the polymer backbone).[24] The reaction conditions for the 2k macrocycle formation were applied directly to the cyclization reaction for the 7k precursor (see Table 1) except the polymer concentration was decreased. The synthetic procedures, SEC chromatograms (Figure S4, Supporting Information) and MALDI−TOF mass spectra (Figures S5 and S6, Supporting Information) for the 7k precursor and macrocycle can be found in the Supporting Information (Section S-C). These results clearly show that the corresponding 7k macrocyclic polymer has been formed efficiently. The crude macrocycle was purified by fractionation and the characterization data are listed in Table 2.

To further test the scope of these procedures, a 17 000 g/mol precursor, α-4-pentenyl-ω-(p-vinylbenzyl)polystyrene, was prepared. The SEC chromatogram for this product is shown in Figure 6; a small amount (7%) of dimer was formed during the reaction of PSLi with p-chloromethylstyrene as discussed previously.[39] The SEC trace of the product from metathesis ring closure of the 17k precursor (see Figure 6) indicated that the macrocyclic polymer was not formed efficiently in methylene chloride after heating for 24 h at 40 °C even at higher dilution, e.g., 4×10^{-5} M versus 1.2×10^{-4} M for the 17000 and 2000 Da precursors, respectively. The peak maximum was not shifted significantly compared to the precursor, but the amount of the higher molecular weight fraction increased considerably (24%). This higher molecular weight fraction is ascribed to an intermolecular metathesis reaction, i.e., acyclic diene metathesis (ADMET).[43] It was envisioned that the efficiency of the intramolecular ring-closure reaction could be favored, relative to competing intermolecular reactions, by utilizing a poorer solvent for the polymer, i.e., by favoring a more compact conformation for the polymer. Since cyclohexane is a theta solvent for polystyrene,[44] the ring closure reaction was investigated in a mixture of methylene chloride and cyclohexane. The SEC chromatogram for 17k macrocyclic polystyrene formation in CH_2Cl_2/C_6H_{12} (1/4, v/v) is compared to that for the analogous reaction in methylene chloride, as well as to that for the linear precursor in Figure 6. In the poorer solvent mixture, the peak maximum has shifted to higher elution volume as expected, and there is less chain-extension (20% versus 7% dimer for the precursor) to form the higher molecular weight fraction.

The efficiency of the macrocyclization was evaluated by comparison of the MALDI−TOF mass spectra for the linear precursor (Figure 7) and the product of the macrocyclization in the mixed solvent (Figure 8). The calculated average mass for a representative peak corresponding to the 144-mer of the α,ω-divinyl precursor is 15,291.6 Da [69.12 (C_5H_9) + 144 × 104.149 (C_8H_8)+117.17 (C_9H_9) + 107.87 (Ag^+)], while the observed peak is at m/z 15 291 after calibration with polystyrene standards; thus, the observed average mass peak at m/z 15 291 is in good agreement with the calculated average monoisotopic mass for the divinyl precursor. Furthermore, analysis of 10

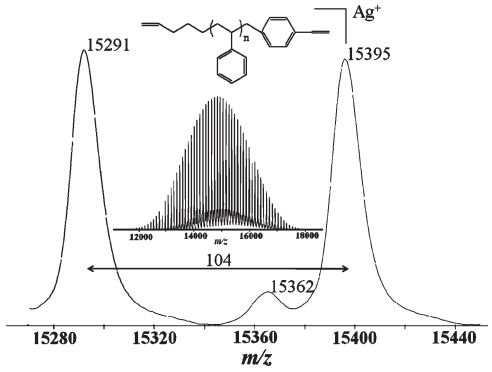

Figure 7. MALDI−TOF mass spectrum of 17k α-4-pentenyl-ω-(*p*-vinylbenzyl) polystyrene.

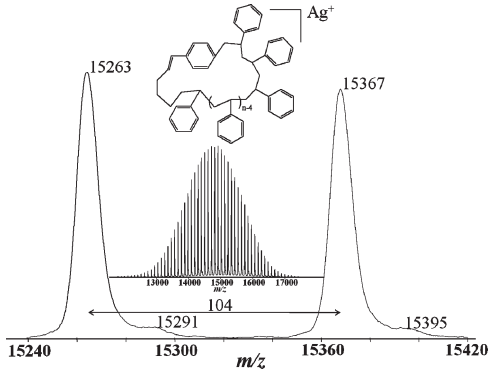

Figure 8. MALDI−TOF mass spectrum of crude 17k macrocyclic polystyrene.

representative peaks in this spectrum (see Table S2, Supporting Information) shows that the average mass difference between observed and calculated values is ± 1 m/z using a 5-point calibration with a 17k polystyrene standard. The small distribution represented by the peak at m/z 15362 has not been assigned. It does not correspond to the most probable impurity, monofunctional polystyrene, $[(C_5H_9) - (C_8H_8)_{146} - (H)\cdot(Ag^+)]$. The calculated average mass for the 146-mer of monofunctional PS is 15384 Da [69.12 (C_5H_9) + 146 × 104.149 (C_8H_8) + 1.01 (H) + 107.87 (Ag^+) = 15383.8 Da]. Considering all the MALDI−TOF mass spectra for the cyclic precursors, it is noteworthy that this impurity was only observed in this sample.

The mass spectrum for the crude product from metathesis macrocyclization exhibits one predominant distribution, with a shoulder being apparent on the high m/z side of each peak, presumably corresponding to the uncyclized, divinyl precursor; for example, the small shoulder at m/z 15,291 can be assigned to the 144-mer precursor as described above. A representative average mass peak at m/z 15,263 corresponds to the 144-mer of the macrocyclic polystyrene; the calculated average mass {[158.24 ($C_{12}H_{14}$) + 144 × 104.149 (C_8H_8) + 107.87 (Ag^+)] = 15,263.6 Da}. Since the 144-mer from the divinyl precursor exhibited a peak at m/z 15291, a difference of m/z 28, the mass spectral results show that the corresponding macrocyclic polymer from the 17 000 Da precursor has been formed very efficiently. Analysis of 10 representative peaks in the MALDI-ToF mass spectrum of the 17k macrocyclic polystyrene (see Table S3, Supporting Information) shows that the average mass difference between observed and calculated values is ± 1 m/z.

The highest molecular weight precursor prepared in this study was 37 000 Da (see Table 1); the synthetic procedure, SEC chromatograms (Figure S7, Supporting Information) and MALDI−TOF mass spectra (Figures S8 and S9, Supporting Information) for the 37k precursor and macrocycle can be found in the Supporting Information (Section S-D). Analysis of 13 representative peaks in the MALDI−TOF spectrum of the 37k divinyl precursor (see Table S5, Supporting Information) shows that the average mass difference between observed and calculated values is ± 1.5 m/z. Analysis of 14 representative peaks in the MALDI−TOF mass spectrum of the 37k macrocycle (see Table S6, Supporting Information) shows that the average mass difference between observed and calculated values is ± 6 m/z with a 5-point calibration using a 35k polystyrene standard. The largest mass difference, including the contributions of end groups and repeating units, between observed and calculated average mass for 37k macrocyclic polystyrene is 6.191 m/z, or 171 ppm. This is less than 200 ppm, which is the mass accurancy specified for linear TOF mass analyzers.[45] It is concluded that the observed masses are in reasonable agreement with the calculated masses. It should be noted once again that it is difficult to define the peak maxima because of the broader distribution observed for high molecular weight, average mass peaks. It is concluded that the mass spectral results are consistent with the efficient formation of the macrocyclic polymer, recognizing that there is significant error in the absolute values of the average peak masses. The crude macrocycle was purified by fractionation and the characterization data are listed in Table 2.

Although there have been numerous previous reports of efficient macrocycle syntheses using chemistries such as click chemistry and ring-closing metathesis as described in the Introduction, this work represents the first time that efficient macrocyclization has been documented by MALDI−TOF mass spectrometry for such a high molecular weight macrocycle of a polymer as stiff as polystyrene. Hoskins and Grayson[22] have reported clean cyclization of relatively flexible polycaprolactone of molecular weight 15 000 g/mol. This polycaprolactone, with 7 atoms per repeat unit, (~900 atoms long) is longer than the 37 000 g/mol polystyrene (~700 atoms long) studied here.

The results reported herein show that ring-closing metathesis (RCM) is a useful, efficient method for synthesis of macrocyclic polymers. This method provides an alternative to methods utilizing click chemistry (see Introduction) and has the advantages of not producing a heterocyclic, in-chain functionality and also generating a macrocycle whose mass is uniquely different from the precursor corresponding to the loss of an ethylene unit. No comprehensive, systematic comparisons of these two methods have been reported;[26,46] however, each method will probably exhibit advantages depending on the specific system being investigated.

■ CONCLUSION

An efficient procedure for the synthesis of well-defined, narrow molecular weight distribution, macrocyclic polystyrenes (M_n 2800−38 000 g/mol) has been described based on the cyclization of α-4-pentenyl-ω-(*p*-vinylbenzyl)polystyrenes using a metathesis catalyst. α,ω-Divinylpolystyrenes with controlled molecular weights and narrow molecular weight distributions

were efficiently prepared using the unsaturated initiator, 4-pentenyllithium, followed by termination with 4-chloromethylstyrene. The efficiency of the ring-closure using Grubb's catalyst, bis(tricyclohexylphosphine)benzylidine ruthenium(IV) chloride, was improved for higher molecular weight precursors by utilizing both higher dilutions and poorer solvent mixtures for the polymers.

■ ASSOCIATED CONTENT

Supporting Information. Information on external calibration of MALDI−TOF MS spectra and SEC, NMR, and MALDI−TOF MS characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

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