5582 *Macromolecules* **2010**, *43*, 5582–5588
DOI: 10.1021/ma902849r

Macromolecules
ARTICLE

Multihydroxyl-Functional Polystyrenes in Continuous Flow

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Received December 28, 2009; Revised Manuscript Received March 28, 2010

ABSTRACT: We describe the synthesis of end-functionalized polystyrenes by living anionic polymerization in a microstructured reactor via termination by acetal-protected functional epoxides. Initiation of styrene polymerization by alkyllithium takes place in a micromixing device with efficient heat and mass transfer properties. A newly developed continuous polymerization−termination sequence enabled quantitative functionalization of the living carbanions by nucleophilic displacement with different, specifically designed glycidyl ethers (ethoxy ethyl glycidyl ether (EEGE), 1,2-isopropylidene glyceryl glycidyl ether (IGG), and *trans*-2-phenyl-1,3-dioxane glycidyl ether (PDGE)). Upon acidic hydrolysis the end-capped polystyrenes release multiple hydroxyl groups (2−3) at the chain end. Temperature and flow rates have been varied to control molecular weights and to optimize the reaction conditions for maximum polymerization and termination efficiency. The polymers were analyzed in detail using NMR spectroscopy, size exclusion chromatography (SEC), and MALDI-ToF-MS. Molecular weights of the samples prepared ranged between 1800 and 9000 g/mol. For all of the novel termination agents full termination was confirmed by MALDI-ToF MS. The approach presented is applicable for a large variety of monomers that are polymerizable by carbanionic polymerization.

Introduction

Carbanionic polymerization is a highly useful technique for the synthesis of polymers with precisely adjustable molecular weights and low polydispersity. Its living character along with negligibility of chain transfer/termination reactions further permits the preparation of specifically chain-end-functionalized polymers. Since Michael Szwarc's pioneering works in the 1950s,[1] both academic and industrial interests have been focusing on the exploration of new synthetic strategies to a large variety of well-defined functional macromolecules.[2] Polymers with functional termini offer vast potential due to the possibilities resulting from reversible ionic association, further chain extension, branching, and (cross)linking with polyfunctional reagents or other polymer chains as well as for the initiation of subsequent polymerizations. Advanced macromolecular architectures with unique structural and physical properties[3,4] (for instance, block copolymers, comblike, cyclic, linear-hyperbranched,[5] and star-branched polymers) can be elegantly obtained from well-defined functional polymer precursors.

A large variety of intriguing materials with supramolecular properties that depend on the nature and position (terminal or in-chain) of the functional groups has been developed.[6] As the interaction at polymer−polymer interfaces in blends or between polymers and surfaces can be tailored by the polymer architecture, functional polymers possess enormous potential for a variety of industrial and academic applications,[7] e.g., dispersion of fillers,[8] transparent impact polystyrene−polybutadiene blends (TIPS),[9] and for the modification of surface properties, that is, adhesion, wettability, biocompatibility, chemical resistance, and hydrophobicity.[10]

Two general strategies are employed to synthesize well-defined, end-functional polymers by living carbanionic polymerization: (i) use of a (usually protected) functional initiator and/or (ii) termination of the polymerization with an electrophilic reagent bearing the desired functionality. Using functional initiators permits quantitative functionalization and facile synthesis of telechelic polymers with (different) functional groups. However, their availability is limited, and solubility in solvents suitable for carbanionic polymerization may sometimes be poor. The termination strategy (ii) has been employed in most cases. Quirk and co-workers have optimized the latter approach by realizing a variety of termination reactions via selective adjustment of reaction parameters like temperature, solvent, and additives to obtain a maximum degree of functionalization.[11]

The most widely used termination reagents are chlorosilane derivatives.[6,12] As an alternative, the reaction with functional diphenylethylenes (DPE) has become popular,[4,13] since the polymer chains remain active for further extension (living functionalization reaction), unless a termination agent is added. Various epoxides[14] have also been used, particularly ethylene oxide (EO), however, in fewer cases than the highly established chlorosilane termination method. Epoxides are of particular interest for the termination of carbanionic polymerization, since they combine pronounced chemical versatility with high reactivity toward nucleophilic attack due to the effect of ring strain. Furthermore, the lithium counterion common in carbanionic polymerization is known to prevent further propagation in epoxide polymerization due to the strong oxygen−lithium aggregation.[15] Quirk et al. took advantage of this behavior in elegant work to realize quantitatively hydroxyl-terminated polystyrene (PS) by reaction of the living chain end with ethylene oxide (EO).[16] Also, propylene oxide[17] and 1,2-epoxybutane[18] have been employed as termination reagents during the past two decades to introduce a single secondary hydroxyl group at the chain end. Additional functionalities can be implemented by using epoxide derivates with protected or unprotected functional groups, depending on the stability toward the highly aggressive living carbanions.[19,20]

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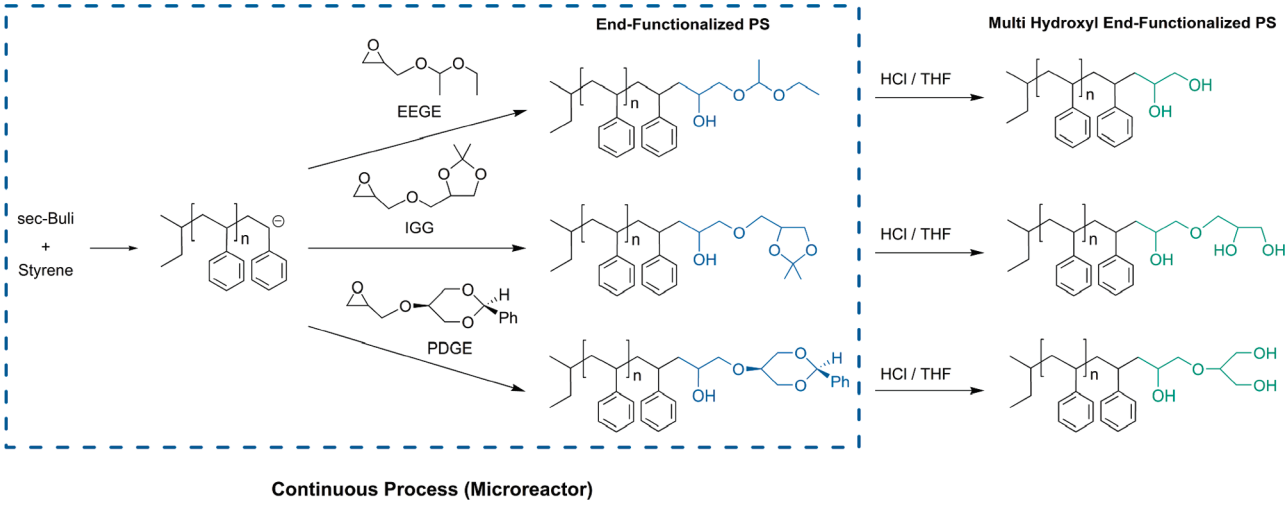
 Published on Web 05/28/2010

Scheme 1. Semicontinuous Synthesis of Multihydroxyl End-Functionalized Polystyrene Using a Microstructured Reactor (HP-IMM)



Glycidyl ethers, a peculiar class of epoxide derivatives, have only been marginally referred to as termination reagents for living carbanionic polymerizations. In an elegant work, Hillmyer et al. reported the termination with methoxy methylene glycidyl ether (MMO) and subsequent use of the generated bis-hydroxy functional polymer as macroinitiators for preparation of ABC miktoarm star terpolymers[21] with unusual morphologies.[22] In a similar manner, Huang et al. prepared three-arm star polymers using ethoxy ethyl glycidyl ether (EEGE) as a termination reagent.[23]

Here we report on the development of an efficient and versatile synthesis protocol for the preparation of well-defined polystyrenes with multiple hydroxyl end groups, using different glycidyl ethers with acetal structures, namely ethoxy ethyl glycidyl ether (EEGE), 1,2-isopropylidene glyceryl glycidyl ether (IGG), and *trans*-2-phenyl-1,3-dioxane glycidyl ether (PDGE) as termination reagents. In accordance with the rapid approach to precisely defined living polystyrene chains previously published by our group,[24] we employed a microstructured reaction system[25] for sequential initiation/polymerization/functionalization within very short times, taking advantage of the dedicated heat and mass transfer characteristics, which are particularly favorable for living polymerization techniques requiring rapid mixing of initiator and monomer as well as efficient heat release due to pronounced exothermic character.[24,26]

Recent studies demonstrate the successful implementation of several polymerization techniques in microdimensional devices, e.g., free radical,[27] controlled radical,[28] anionic,[24,29] and cationic[30] polymerizations. Beers et al. performed the anionic polymerization of styrene in a low-cost aluminum−kapton microfluidic device investigating different 2D designed flow channels.[31] Pertinent advances have also been achieved in the field of hyperbranched polymers[32] and dendrimers.[33]

However, only little attention has been paid to the potential of continuously operating microstructured reactors for the sequential synthesis of multiple functionalized polymers and the anionic polymerization of vinyl monomers with subsequent functionalization in continuous flow. Within the scope of our investigations, we concentrated on the development of a versatile process for the rapid synthesis of novel tailor-made end-functional polymers by living carbanionic polymerization, using specifically designed glycidyl ethers as termination reagents that release multiple hydroxyl groups upon facile acidic hydrolysis. An overview of the epoxides employed and the functionalization strategies introduced is shown in Scheme 1.

Experimental Section

Reagents. All solvents and reagents were purchased from Acros Organics and used as received unless otherwise stated. Tetrahydrofuran (THF) for polymerization was distilled from sodium/benzophenone under reduced pressure (cryo-transfer). Styrene was dried over calcium hydride (CaH_2) and cryo-transferred prior to use. *sec*-Butyllithium (*sec*-BuLi, 1.3 M, Acros) was used as received, and the concentration of the initiator was determined by the Gilman double titration method.[34] *n*-Hexane and CaH_2 were purchased from Fluka and used as received. Chloroform-*d* and benzene-d_6 were purchased from Deutero GmbH and stored over molecular sieves (3 Å).

Instrumentation. ^{1}H NMR spectra were recorded at 400 MHz on a Bruker AMX 400 and were referenced internally to residual proton signals of the deuterated solvent ($CDCl_3$, benzene-d_6). Field desorption mass spectra were measured on a Finnigan MAT 95. Size exclusion chromatography (SEC) measurements were carried out in THF on an instrument consisting of a Waters 717 plus autosampler, a TSP Spectra Series P 100 pump, a set of three PSS SDV columns (104/500/50 Å), and RI and UV detectors. All SEC diagrams rely on the RI detector signal, and the molecular weights refer to linear polystyrene (PS) standards provided by Polymer Standards Service. Matrix-assisted laser desorption and ionization time-of-flight (MALDI-ToF) measurements were performed on a Shimadzu Axima CFR MALDI-TOF mass spectrometer using dithranol (1,8,9-trishydroxyanthracene) as matrix.

Synthesis of Glycidyl Ethers. *Ethoxy Ethyl Glycidyl Ether* (*EEGE, **1***). EEGE was synthesized as reported by Fitton et al.[35] Glycidol was added to an excess of ethyl vinyl ether and catalytic amounts of *p*-toluenesulfonic acid to obtain the desired product (yield: 90%).

DL-1,2-Isopropylidene Glyceryl Glycidyl Ether (*IGG, **2***). IGG was synthesized according to a recently published procedure[36] by phase-transfer reaction of epichlorohydrin and solketal (isopropylidene glycerol) in benzene and 50% KOH solution as solvents. Tetrabutylammonium bromide (TBAB) was added and served as catalyst (yield: 51%).

trans-2-Phenyl-1,3-dioxane Glycidyl Ether (*PDGE, **3***). 4.1 g (23 mmol) of 5-hydroxy-2-phenyl-1,3-dioxane (HPD)[37] was dissolved in 20 mL of benzene, 20 mL of 50% KOH, and 0.74 g (2.3 mmol) of TBAB were added. After cooling the mixture to 10 °C, epichlorohydrin was slowly added via syringe. The reaction mixture was stirred at room temperature for 48 h, diluted with diethyl ether, and washed three times with water, saturated aqueous $NaHCO_3$, and saturated aqueous NaCl. After drying over $MgSO_4$, diethyl ether and excess epichlorohydrin were removed *in vacuo*. The crude product was purified via column chromatography (silica, chloroform:ethyl acetate 5:1, R_f = 0.45). 1.5 g (6.3 mmol, yield: 30%) of PDGE was obtained and characterized by ^{1}H NMR spectroscopy and field desorption mass spectrometry (FD-MS). ^{1}H NMR (300 MHz, C*D*Cl_3,

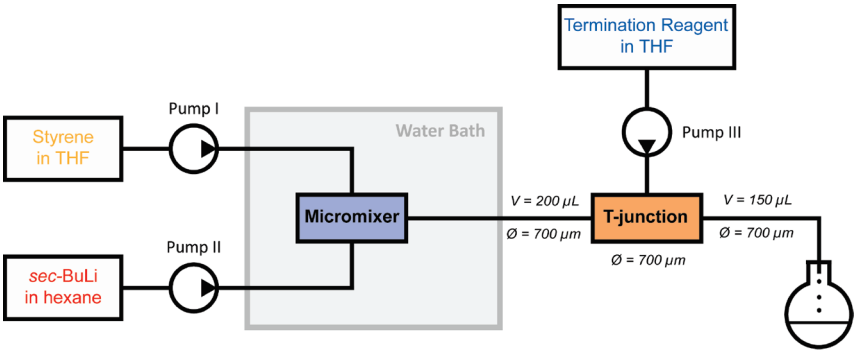


Figure 1. Schematic reactor setup for polymerization of styrene with direct subsequent termination by glycidyl ethers (micromixer: HP-IMM).

δ in ppm): 7.43 (m, 5H, C_6H_5), 5.57 (s, 1H, C*H* acetal), 4.37 (m, 2H, CH_2 1,3-dioxane), 4.08 (m, 2H, CH_2 1,3-dioxane), 3.97 (dd, 1H, CH_2 glycidol), 3.55 (q, 1H, CH_2 glycidol), 3.46 (m, 1H), 3.24 (m, 1H, C*H* epoxide), 2.83 (t, 1H, CH_2 epoxide), 2.68 (q, 1H, CH_2 epoxide). ^{13}C NMR (75 MHz, $CDCl_3$, δ in ppm): 138.0 (quart. *C* aromatic), 128.9 (*C*H aromatic), 128.2 (*C*H aromatic), 126.1 (*C*H aromatic), 101.3 (tert. *C*H acetal), 71.0 (*C*H 1,3-dioxane) 69.4 (CH_2 1,3-dioxane) 68.6 (CH_2), 51.2 (*C*H epoxide), 44.2 (CH_2 epoxide). FD-MS: 235.9 g/mol.

Microstructured Reactor. A continuous flow reaction setup (Scheme 1) equipped with a micromixer was employed for the synthesis of end-functionalized polystyrenes. A stainless steel high-pressure slit interdigital micromixer (HP-IMM, provided by the Institut für Mikrotechnik Mainz (IMM)) with an internal volume of 15 μL was used for fast and efficient mixing of monomer and initiator realized by multilamination mixing mode, combined with geometric and hydrodynamic focusing.[38] The micromixer was immersed in a water bath at predefined temperature and equipped with two reactant inlets and one outlet. After mixing of monomer and initiator within several milliseconds, the reaction mixture passed a short stainless steel capillary residence tube (for details cf. Figure 1) and was combined with the corresponding glycidyl ether (separate flow tube) in a T-junction (diameter = 700 μm). The residence tube behind the T-junction was connected to a degassed vessel for sample collection. Flow rates were controlled via HPLC pumps (Knauer WellChrom K-501, inert 10 mL pump heads with ceramic inlays).

Synthesis of Hydroxyl-Functionalized Polystyrenes. *Exemplary Synthesis Procedure for PS-EEGE-3.* Prior to the polymerization reaction, THF was pumped through the microstructured reactor setup for ~10 min at 0.5 mL/min via all three HPLC pumps to rinse off residual impurities. The water bath was kept at room temperature, and a solution of purified styrene (1.5 M) in dry THF was kept under argon in a flask covered with a septum. Into a second flask containing dry hexane, 3.8 mL *sec*-BuLi was added via syringe directly before starting the reaction (0.05 M). The third flask contained a solution of purified EEGE (0.1 M) in THF. The three flasks were connected to the HPLC pumps via PTFE tubes transfixed through the septa. The connection tube between micromixer and T-junction was 50 cm in length and 700 μm in diameter, corresponding to an internal volume of ~200 μL. A schematic overview of the general setup is shown in Figure 1.

Prior to the polymerization start, pump II (initiator) was activated and the assembly was flushed with *sec*-BuLi solution to eliminate residual impurities. In order to initiate the continuous process, pumps I (monomer) and II (initiator) were activated with flow rates of 1 mL/min. After the characteristic reddish color appeared at the outlet, pump III was activated with a flow rate of 1 mL/min to combine the termination reagent and the reaction mixture within the T-junction. Full monomer conversion was achieved after 6 s, and the end-capped polymer was recovered from a short outlet tube (50 cm length, 700 μm diameter, internal volume ~200 μL) connected to the T-junction. PS-EEGE-3 was precipitated into methanol and dried in vacuum at room temperature for 12 h.

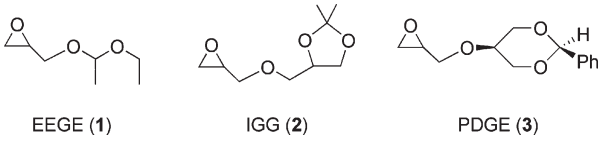


Figure 2. Glycidyl ethers/acetals used as termination reagents in the continuous polymerization−termination sequences.

All polymer samples prepared have been produced by an analogous procedure. Adjusting the flow rates via the control elements of the HPLC pumps or selecting different concentrations permits convenient variation of molecular weights of the materials prepared.

Synthesis of Multihydroxyl-Functionalized Polystyrene. 500 mg of the end-capped PS was dissolved in 20 mL of THF and 3 mL of 2 M HCl. After refluxing of the solution for 8 h, the reaction mixture was diluted with chloroform and washed with saturated aqueous $NaHCO_3$ and water. After drying the organic phase with $MgSO_4$, all solvents ($CHCl_3$, THF) were removed under reduced pressure. The samples were precipitated into MeOH and dried at room temperature for 12 h.

Results and Discussion

Three different glycidyl ethers (Figure 2) with acetal or ketal protecting group were used to terminate the living anionic polystyrene chains in continuous flow, aiming at novel multihydroxyl end-functionalized polymer structures: EEGE (**1**), IGG (**2**), and PDGE (**3**), a novel glycidyl ether that was prepared from epichlorohydrin using TBAB as a phase transfer catalyst. This compound offers the unique possibility to introduce one secondary and two primary protected hydroxyl groups via a single functionalization/deprotection sequence.

The different epoxide termination agents were obtained in high purity (see Supporting Information, Figures S7 and S8), which is essential for quantitative chain-end functionalization of living carbanionic polymers. Strong aggregation of the lithium counterion with alkoxides prevents further oxyanionic propagation,[15] rendering the synthesized glycidyl ethers suitable for quantitative and simultaneous end-capping of the living carbanions.

Utilization of the micromixer-based reaction system permits rapid reactant mixing and offers the possibility to apply reaction conditions (room temperature) that are not applicable in conventional glass equipment. Thus, significantly faster reaction kinetics can be realized. The technique is feasible, unless very high molecular weights are required. The stainless steel setup shows excellent chemical resistance toward the highly aggressive carbanions and hence provides an ideal platform for rapid living anionic polymerization sequences. For comparison, classical

Table 1. Characterization Data of End-Functionalized PS Samples Prepared by Anionic Polymerization with Subsequent Termination in a Microstructured Reaction Setup

sample	T/°C	t^a	$M_n{}^b$	$M_n{}^c$	$M_n/M_w{}^c$
PS-EEGE-1	25	12	1900	1800	1.14
PS-EEGE-2	40	12	1900	1900	1.15
PS-EEGE-3	40	10	3100	3000	1.14
PS-EEGE-4	25	5	4300	3900	1.13
PS-EEGE-5	40	8	3800	4500	1.26
PS-EEGE-6	50	8	3800	6400	1.18
PS-IGG-1	25	6	1900	1900	1.22
PS-IGG-2	60	12	2500	2300	1.18
PS-IGG-3	25	12	2600	2900	1.28
PS-IGG-4	25	8	3800	4100	1.29
PS-IGG-5	25	10	3900	5000	1.21
PS-IGG-6	60	8	5000	5300	1.23
PS-IGG-7	25	8	5200	7700	1.22
PS-PDGE-1	25	12	2800	3600	1.26
PS-PDGE-2	25	12	5000	4100	1.36
PS-PDGE-3	25	8	7500	8800	1.24

[a] Residence time in seconds. [b] Theoretical value of the number-average of the molecular weight in g mol^{-1}. [c] Molecular weight in g mol^{-1} and molecular weight distribution characterized by SEC in THF.

batch methods for carbanionic polymerizations are often labor-intensive and in many cases require "high vacuum" or "break-seal" methods as well as individually manufactured glass reactors.[39] Residence times required for full conversion of styrene in the micromixer-based system are generally below 15 s without loss of control over the polymerization compared to oftentimes prolonged reaction times of typically 2−3 h in batch reactors. The temperature dependency of the continuous flow polymerization has also been studied by increasing the temperature to 60 °C. However, no significant deviation with respect to the polymer properties (M_n, PDI) has been observed.

Initiation of styrene polymerization with *sec*-BuLi in the micromixer at room temperature, using THF as a solvent, results in an extremely fast propagation reaction ($t_{1/2}$ < 0.5 s).[40] Full monomer conversion is achieved within seconds,[24,26] before the living chain ends are reacted with the unsubstituted carbon of the highly strained epoxide ring. A short outlet tube (for details cf. Figure 1) is sufficient for reaction of all living polymer chains with the termination reagent before leaving the reactor. A color change of the reaction mixture (reddish to light yellow), resulting from the termination of living carbanions, can be observed. By adjusting the ratio of styrene and *sec*-BuLi flow rates, the degree of polymerization was readily varied during the ongoing experiment. Thus, the micromixing device provides convenient access to a variety of structurally different polymers without modifying the setup within one run. Subsequent to the continuous polymerization/functionalization sequence, the protecting groups are cleaved by acidic hydrolysis to afford multihydroxyl end-functionalized polymers.

Characterization by size exclusion chromatography (SEC) yielded reasonable agreement between theoretical and experimental molecular weights, revealing narrow to moderate and monomodal molecular weight distributions (MWDs) (M_w/M_n < 1.30, mostly < 1.25; Table 1). No dependence of molecular weights and PDI on the temperature was observed in the temperature range between 25 and 60 °C. Figure 3 depicts the SEC diagrams of IGG-terminated polystyrenes with monomodal MWDs, evidencing the remarkable degree of control over the polymerization under the applied continuous flow conditions.

The MWDs of the epoxide-terminated polymers obtained by the continuous approach presented herein are generally slightly broader than those realizable in classical batch reactors (typically < 1.1, often 1.01−1.03). A possible explanation can be found in the slightly incontinuous flow of the HPLC pumps, which

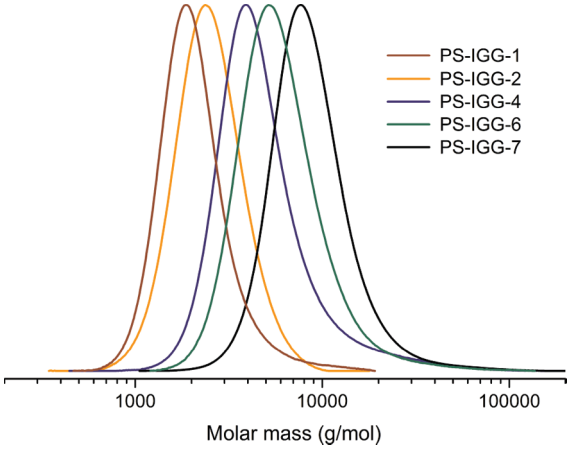


Figure 3. MWDs determined via SEC of selected PS-IGG samples (THF, RI signal).

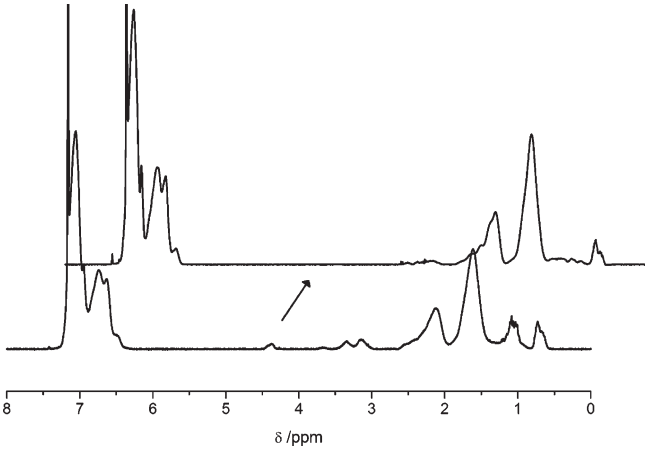


Figure 4. ^{1}H NMR spectra of PS-EEGE (bottom: PS-EEGE-2; top: deprotected PS-EEGE-2 (PS-EEGE$_d$-2); both spectra were measured in benzene-d_6 as solvent.

results in temporary deviations from the adjusted stoichiometry. Taking into account the significantly reduced experimental effort using the continuous device, the micromixer-based system provides an alternative for carbanionic batch polymerization, when very narrow MWDs with PDIs below 1.05 do not represent a necessity, as it applies for a wide variety of applications.[41]

^{1}H NMR spectroscopy was employed to study the functionalization as well as monomer conversion. Figure 4 (bottom) represents the ^{1}H NMR spectrum of PS-EEGE-2. The expected signals reflecting the polystyrene backbone (aromatic signals at 7.3−6.3 ppm and aliphatic signals at 2.6−0.8 ppm) are clearly visible. Referencing the respective signals to the six methyl proton signals of the initiator *sec*-BuLi (0.72 ppm) permits to estimate the functionalization efficiency. The acetalic proton (4.38 ppm) of the end group attached to the polymer generates a readily distinguishable signal that can be separately integrated. The respective values were close to 1 in all cases, indicating a high degree of functionalization. However, end-group analysis using ^{1}H NMR spectroscopy becomes increasingly problematic at elevated molecular weights due to the diminishing end-group signal intensity.

It is known from the literature that the regiochemistry of reactions between living polystyrene and epoxide compounds depends on the steric and electronic nature of the termination reagent.[17−20] For instance, the reactions of poly(styryl)lithium with propylene oxide and 1,2-butene oxide are regioselective due to pronounced steric effects of the methyl or ethyl group,

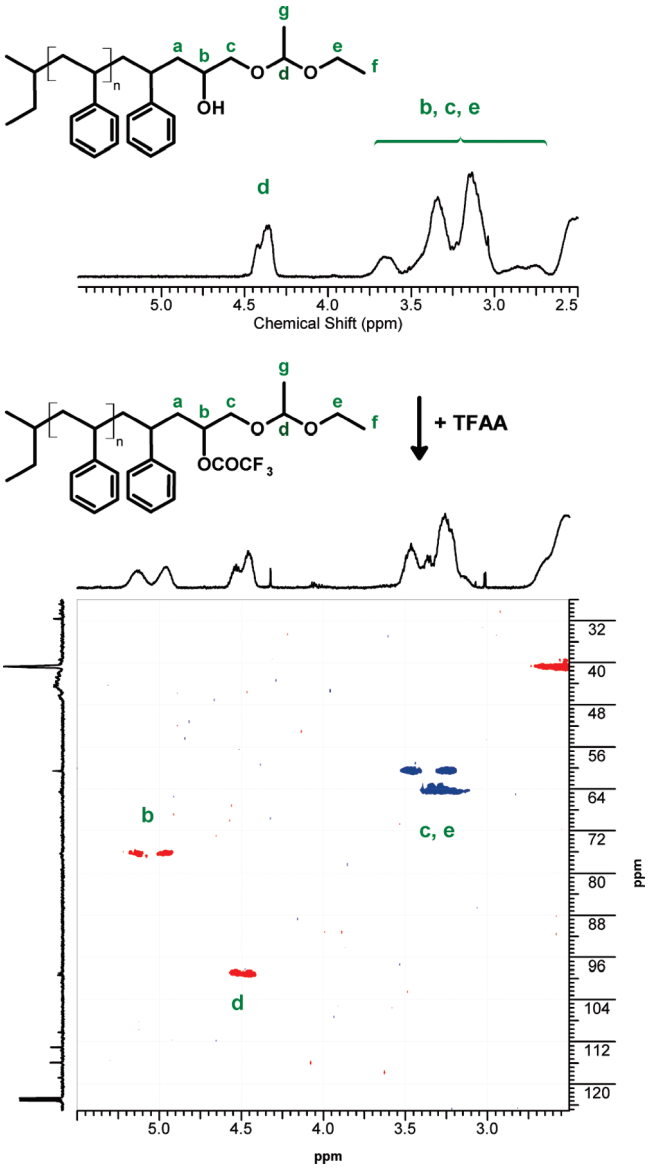


Figure 5. Top: section of ^{1}H NMR spectrum of PS-EEGE-2. Bottom: HSQC spectrum of PS-EEGE-2 after reaction with trifluoroacetic anhydride (TFAA). Phase information is given by coloration of cross peaks (red: methyl, methine; blue: methylene).

respectively. Nucleophilic attack at the least hindered carbon atom predominantly results in formation of the secondary alcohol. In contrast, when employing styrene oxide as a termination reagent, no regioselectivity can be observed due to the parallel influence of both steric and electronic effects. In the case of reacting poly(styryl)lithium with the different glycidyl ethers reported herein, regioselectivity was expected due to the steric hindrance of the bulky moieties attached to the epoxide ring. Two-dimensional (2D) NMR spectroscopy was employed to gain insight with respect to the selectivity of the reactions. Figure 5 represents a section of the HSQC spectrum of PS-EEGE-2 in benzene-d_6 after reaction with trifluoroacetic anhydride (TFAA), adding a small amount of pyridine-d_5 as acid scavenger to prevent cleavage of the protecting group. The cross peaks **b**, generated by the methine groups, are shifted downfield (5.0−5.5 ppm) in the corresponding ^{1}H NMR spectrum due to ester formation. Owing to the presence of a mixture of diastereomers, two distinct methine signals are generated. The absence of any downfield-shifted methylene signals (blue) indicates that regioselective attack of poly(styryl)lithium took place exclusively at the least hindered carbon atom of EEGE, and thus no primary alcohol was formed. Furthermore, the ^{1}H−^{1}H-COSY spectrum (see Supporting Information Figure S5) illuminates the coupling between **b** and adjacent methylene groups **a** and **c**. Taking into account the additional steric constraints of the other termination reagents, similarly regioselective nucleophilic displacement reactions can be safely assumed for all epoxide termination reagents of this study.

The spectra of both the protected and deprotected polymer (PS-EEGE-2) are depicted in Figure 4. Complete disappearance of the acetalic proton d (4.38 ppm) as well as the methyl group signals (1.06) confirms quantitative deprotection of the acetalic end groups. It has to be emphasized that the deprotection times are considerably prolonged compared to water-soluble polymers,[42] which can be explained by the nonpolar character of the polystyrene backbone, shielding the acetal group from the deprotecting reagent. Additional NMR spectra of PS-IGG and PS-PDGE polymers before and after deprotection are given in Figures S3 and S4 of the Supporting Information. As expected, no significant change in molecular weight and MWD has been observed after cleavage of the protecting groups (SEC).

As indicated above, NMR spectra cannot provide sufficient proof for quantitative terminal functionalization of the polymers, particularly at elevated degrees of polymerization. Matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-ToF MS) as a crucial characterization method for the detailed investigation of end-functional polymers was thus applied in order to obtain unequivocal evidence for the high functionalization efficiency of the method. Quantitative functionalization of polystyrenes capped with the three different glycidyl ethers was demonstrated by MALDI-ToF MS, using silver trifluoroacetate as cationizing agent and dithranol (1,8,9-trishydroxyanthracene) as matrix. Figure 6 shows two MALDI-ToF spectra of IGG- and PDGE-terminated polystyrene. The spectrum of PS-IGG (left) reveals only one distribution mode, which is unambiguously assigned to IGG-functionalized polystyrene. The most intense isotopic mass species appear 3 units higher than the monoisotopic peak, and one representative mass peak at m/z 2541.6 corresponds to the 21-mer of PS-IGG-3 (C_4H_9-$(C_8H_8)_{21}$-$C_9H_{17}O_4\cdot Ag^+$); calculated isotopic mass = 2541.4 Da. Similar conclusions apply for the spectrum on the right, representing PS-PDGE-1 with a single distribution mode that can clearly be assigned to the desired polymer. The representative mass peak (28mer: C_4H_9-$(C_8H_8)_{21}$-$C_{13}H_{17}O_4\cdot Ag^+$, 3317.7 Da) is in very good agreement with the calculated value (3317.8 Da). In both cases the mass difference between each signal represents the molecular mass of the monomer (104.1 Da). Furthermore, it has to be emphasized that peaks corresponding to the protonated, nonfunctional polystyrene (PS-H: 22mer = 2457.4 Da or 31mer = 3394.7 Da) are absent in both spectra, confirming the quantitative functionalization of polystyrene with IGG and PDGE.

In order to confirm that nonfunctionalized PS-chains would be detected in the presence of the functionalized PS-samples, mixtures containing end-functional and nonfunctional polystyrenes have been subjected to MALDI-TOF measurements. In this case, in 1:1 blends nearly identical detection intensities of both series of signals were observed (see Supporting Information Figure S9), and therefore similar desorption and ionization properties of the different polystyrene types can be safely assumed.

MALDI-ToF investigation of the PS-EEGE sample series confirmed quantitative functionalization, resulting in analogous single molecular weight distributions (see Supporting Information Figure S6). Detailed MALDI ToF studies with the deprotected polymers confirmed results of the ^{1}H NMR spectra, evidencing successful cleavage of the protecting groups and full functionalization (see Supporting Information Figure S6).

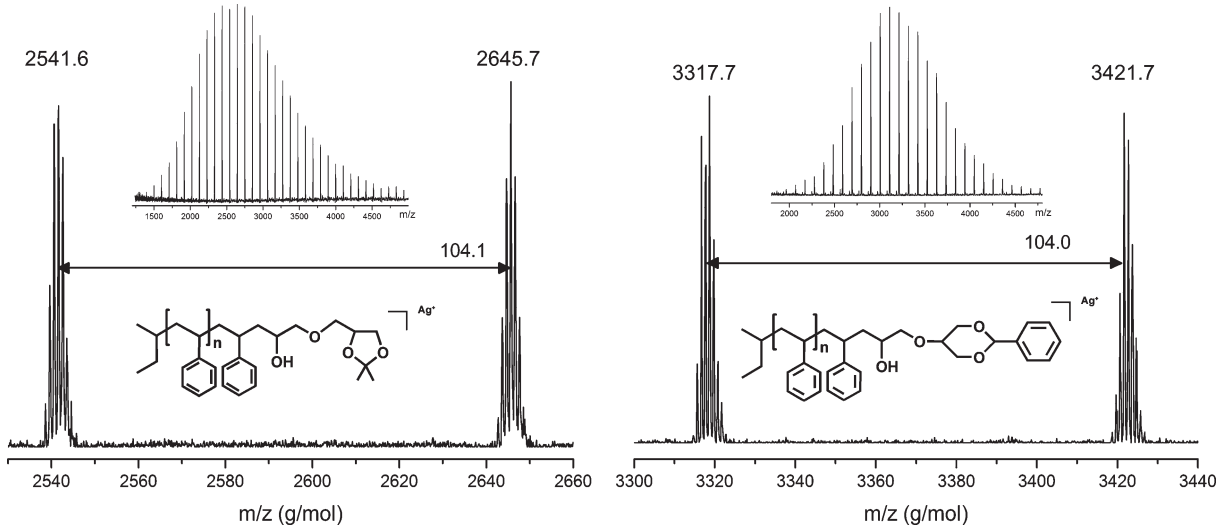


Figure 6. MALDI-ToF mass spectra of end-functionalized polystyrene synthesized in continuous flow: PS-IGG-3 (left), PS-PDGE-1 (right).

Conclusion

We have developed a semicontinuous strategy for the rapid preparation of multihydroxyl-functional polystyrenes, capitalizing on the high stability of the acetal-protecting groups of the protected glycidyl ethers toward strong bases. The synthetic approach presented relies on a continuously operating microstructured reaction device for living carbanionic polymerization and termination with specifically tailored glycidyl ethers, followed by deprotection of the introduced end-group moieties.

Adjustment of molecular weights as well as chemical nature of the end group can be achieved by alteration of the flow rates in a single experiment without interrupting the continuous flow process. Full styrene monomer conversion was achieved within several seconds by working at room temperature in a polar solvent, usually THF. The functional polymers were thus obtained in very short reaction times without having to resort to tedious postpolymerization protocols or purification steps in order to yield pure and quantitatively functionalized materials. The acetal and ketal protecting groups of the employed termination reagents are stable toward the highly reactive carbanions and can be cleaved under acidic conditions.

The general termination methodology presented herein also provides a method for rapid and cost-efficient polymer screening with respect to novel end-functionalized materials. By tailoring the glycidyl ethers by means of standard organic synthesis protocols, a large variety of terminal units at vinyl polymers with multiple end groups and intriguing properties can be realized. The respective materials can be further used as macroinitiators for complex macromolecular architectures, such as miktoarm star polymers, block copolymers, and graft polymers. Depending on monomer and termination reagent, such end-functional polymers are also promising for the specific adjustment of surface and interfacial properties. Use of several monomer/termination reagent combinations can rapidly afford polymer libraries, permitting to screen a wide range of material properties (wettability, hydrophobicity, chemical resistance, biocompatibility). A detailed study of other carbanionic polymerization reactions with respect to protected glycidyl ether termination and functionalization is currently in progress and will be reported in due course.

Acknowledgment. C.T. thanks the POLYMAT Graduate Class of Excellence as well as MPGC (Max Planck Graduate Center with Johannes Gutenberg University) for fellowships and financial support. D.W. acknowledges the Fonds der Chemischen Industrie (FCI) for a Ph.D. fellowship. We also thank the IMM (Institut für Mikrotechnik Mainz) for providing the micromixer equipment.

Supporting Information Available: Additional data, MALDI-ToF, NMR, and SEC results (Figures S1−S9, Table 1) demonstrating monomodal molecular weight distributions and complete functionalization. This material is available free of charge via the Internet at http://pubs.acs.org.

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