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Facile Synthesis of Functional Periodic Copolymers: A Step toward Polymer-Based Molecular Arrays.

Marie-Alix Berthet, Zoya Zarafshani, Sebastian Pfeifer, and Jean-François Lutz*

Research Group Nanotechnology for Life Science, Fraunhofer Institute for Applied Polymer Research, Geiselbergstrasse 69, Potsdam 14476, Germany

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ABSTRACT: A step-growth strategy was investigated for preparing functional periodic copolymers. Functional heterotelechelic α-alkyne, ω-azido poly(styrene-*co*-*N*-substituted maleimide) precursors ($M_n \approx 2500$ g·mol^{-1}) have been prepared and subsequently polymerized by copper-catalyzed azide−alkyne cycloaddition (CuAAC). These precursors have been first synthesized by sequential atom transfer radical copolymerization of styrene and a *N*-substituted maleimide (i.e., benzyl maleimide, *N*-(2-(amino-*t*BOC)-ethylen)-maleimide, or benzyl *N*,*N*-maleoylglycinate) initiated by 3-(1,1,1-trimethylsilyl)-2-propynyl 2-bromo-2-methylpropanoate. In this approach, styrene homopolymerization was first started, and a discrete amount of the maleimide comonomer (e.g., 1 equiv as compared to initiator) was added when styrene half-conversion was reached. This controlled maleimide addition resulted in the formation of well-defined polystyrene segments containing a functional maleimide in the middle of their chains (i.e., in average 1 unit per chain). Subsequently, the sequence-controlled copolymers poly(styrene-*co*-*N*-substituted maleimide) have been transformed into reactive heterotelechelic polymers. Various synthetic pathways have been compared for preparing these reactive intermediates. Ultimately, these heterotelechelic precursors were polymerized by CuAAC. ^{1}H NMR and SEC evidenced the formation of high-molecular-weight periodic copolymers.

Introduction

The field of macromolecular engineering has virtually exploded during the last two decades.[1] In particular, very significant advances have been made in the design of complex macromolecular architectures (e.g., block copolymers, dendrimers, star polymers).[2] As a consequence, a wide range of innovative polymer-based nanomaterials have been recently developed.[3] These novel structures show great promises in emerging applications such as nanoelectronics, photonics, biotechnologies, and alternative energies.

Yet, these current advanced technologies will certainly become obsolete in some years. What is then the next step after polymer nanotechnology? Actually, nature gives an obvious answer to this question. Indeed, complex biological assemblies rely for the most part on polymers of controlled microstructure (i.e., tacticity and sequences) rather than controlled architecture. This simple strategy permits to control biomaterials properties way below the nanoscale.[4] Therefore, it seems plausible that synthetic polymers with controlled microstructures may play an important role in the technologies of the future.[5,6] In this context, we and others recently studied some routes for controlling sequences and tacticity in synthetic polymer chemistry.[7]

For instance, we recently reported a simple method for controlling comonomer sequence distributions in a radical chain-growth polymerization.[8,9] This concept relies on the atom transfer radical copolymerization (ATRP) of functional *N*-substituted maleimides with styrene. This copolymerization is a controlled radical process, which combines two unique kinetic features: (i) all polymers chains are growing simultaneously[10,11] and (ii) the cross-propagation of the comonomers is highly favored as compared to homopolymerization.[12] Therefore, discrete amounts of *N*-substituted maleimides (e.g., 1 equiv as compared with initiator) are consumed extremely fast in the copolymerization process and are therefore locally incorporated in narrow regions of the growing polystyrene chains. Typically, if a single equivalent of *N*-substituted maleimides is used in the copolymerization feed, short copolymer sections containing on average one or two functional maleimide units are preferentially formed.[9] Furthermore, the position of the *N*-substituted maleimides in the polystyrene chains can be kinetically controlled by adding them at desired times during the course of the polymerization. This method is actually very versatile and can be applied to a wide variety of *N*-substituted maleimides. For instance, we screened in a previous article a library of 20 different maleimides bearing various functional groups.[9] In most cases, the functional *N*-substituted maleimides could be efficiently incorporated in the polystyrene chains.

Moreover, this concept was utilized for preparing macromolecules with programmed sequences of functional comonomers.[8] For example, we demonstrated that four different *N*-substituted maleimides could be consecutively added during the atom transfer radical polymerization of styrene. Indeed, the formed copolymers are not strictly sequence-defined at the molecular level (i.e., they still exhibit a sequence distribution). However, they undoubtedly possess a preprogrammed distribution of functional side groups along the polymer backbone. Therefore, this straightforward copolymerization strategy could be used to prepare 1D functional arrays on linear polymer chains. However, these reactions remain challenging if one intends to create long sequences of functional comonomers. For instance, it seems difficult to control kinetically the addition of five maleimides or more without automated assistance (e.g., online monitoring of monomer conversions and automated maleimide additions). Still, some chemical means could be used to circumvent these limitations. One possibility would be, for example, to assemble or

*Corresponding author. E-mail: lutz@iap.fhg.de.

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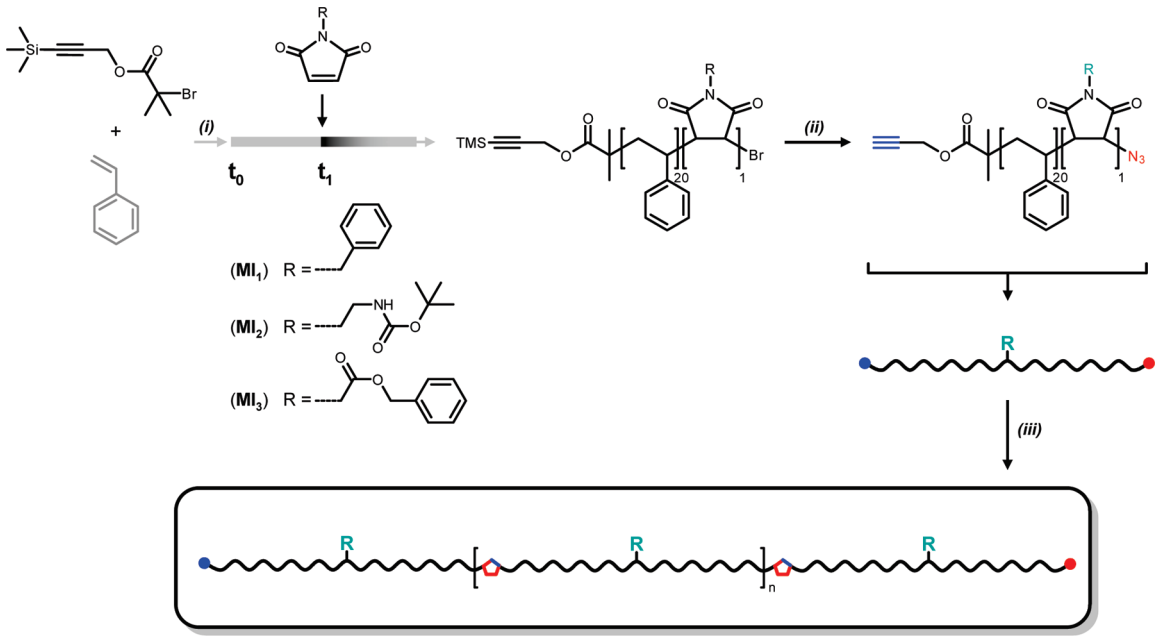
Scheme 1. General Strategy for Preparing Functional Periodic Copolymers: (Top) Synthesis of Functionalized Heterotelechelic Copolymers; (Right) Step-Growth "Click" Coupling of the Formed Copolymers[a]



[a] Experimental conditions: (i) CuBr, PMDETA, bulk, 110°C; (ii) various possible pathways; (iii) CuBr, PMDETA, THF, RT.

to polymerize short sequence-controlled oligomers (i.e., stepwise ligation or periodic copolymerization).[6,13]

In the present article, a simple step-growth strategy was investigated for synthesizing high-molecular-weight polymers containing periodic functional motifs (Scheme 1). In this approach, short polystyrene segments containing functional units (e.g., benzyl, FmocNH- or *t*-butyl ester) in the middle of their chains have been first synthesized using the kinetic strategy described above. Subsequently, these well-defined oligomers have been transformed into reactive α-alkyne, *ω*-azido heterotelechelic polymers. The copper-catalyzed "click" cycloaddition of azides and terminal alkynes was selected for the step-growth chemistry because it has been shown to be an effective tool for macromolecular ligation.[14] In particular, Matyjaszewski and coworkers[15,16] and Drockenmuller and coworkers[17] demonstrated elegantly that step-growth "click" polymerizations generally proceed in high yields. However, copper-catalyzed azide−alkyne cycloadditions (CuAAC) have not been exploited so far in periodic copolymerizations. Herein, we describe the "click" synthesis and characterization of functional periodic copolymers.

Experimental Part

Chemicals. Copper(I) bromide (Aldrich, 99%), styrene (Aldrich, 99%), *N*,*N*,*N*′,*N*′,*N*″- pentamethyldiethylenetriamine (PMDETA) (Aldrich, 99%), *N*-benzylmaleimide (Aldrich, 99%), tetrabutylammonium fluoride (TBAF) (Aldrich, 1,0 M solution in tetrahydrofuran), and sodium azide (Aldrich, 99%) were used as received. 3-(1,1,1-Trimethylsilyl)-2-propynyl 2-bromo-2-methylpropanoate,[18] *N*-(2-(amino-*t*BOC)-ethylen)-maleimide,[19] and benzyl *N*,*N*-maleoylglycinate[20] were synthesized as described in the literature.

Example of Atom Transfer Radical Copolymerization of Styrene and a Functional *N*-Substituted Maleimide.[9] Copper bromide (0.1 equiv) and 3-(1,1,1-trimethylsilyl)-2-propynyl 2-bromo-2-methylpropanoate (1 equiv) were added in a dry Schlenk tube, which was afterward sealed with a septum and purged with dry argon for a few minutes. Then, degassed styrene (20 equiv) was added with a degassed syringe through the septum. Lastly, PMDETA (0.1 equiv) was added with a precision syringe. The mixture was heated at 110 °C in an oil bath for several hours. The functional *N*-substituted maleimides were added during the course of the polymerization through the septum with a degassed syringe. The studied maleimides are solids and were therefore dissolved in small amounts of degassed toluene prior to addition. The experiment was stopped by opening the flask and exposing the catalyst to air. The final mixture was diluted in a small amount of THF and subsequently precipitated in methanol. The precipitated polystyrene was filtered and dried under vacuum.

Deprotection of the α-Trimethylsilyl-Alkyne End Groups of the Copolymers. TMS-deprotection of the copolymer chain ends was performed in THF (0.01 M solution) in the presence of TBAF, as previously described.[18,21] The reaction mixture was stirred overnight at room temperature. Afterward, the copolymer samples were precipitated in methanol and dried under vacuum.

Nucleophilic Substitution of the *ω*-Bromo End Groups of the Copolymers. The procedure for transforming bromide end-functional polystyrene into azide end-functional polystyrene was adapted from the literature.[22,23] Sodium azide (1.1 equiv) and the bromine end-functional copolymer (1 equiv) were dissolved in *N*,*N*-dimethyl formamide (DMF) (copolymer concentration = 0.06 mol·L^{-1}). The reaction mixture was stirred at room temperature for ~3 h. Afterward, the raw experimental mixture was diluted in chloroform, and DMF was extracted with water. The organic phase was reconcentrated in vacuo. Ultimately, the copolymer was precipitated in methanol and dried under vacuum.

Synthesis of Periodic Copolymers via Step-Growth "Click" Coupling of α-*ω*-Heterotelechelic Copolymers. Copper bromide (0.8 equiv) and the α-alkyne, *ω*-azido copolymer (1 equiv) were added to a Schlenk tube, which was afterward sealed with a septum and purged with dry argon for a few minutes. Then, degassed THF was added with a degassed syringe through the septum. Lastly, PMDETA (0.8 equiv) was added with a precision syringe. The reaction mixture was then stirred for 24 h at room temperature. The experiment was stopped by opening the flask and exposing the catalyst to air. The raw mixture was diluted in a small amount of THF and poured dropwise in methanol. The precipitated periodic copolymer was filtered and dried under vacuum.

Measurements and Analysis. *Size Exclusion Chromatography* (*SEC*). Molecular weights and molecular weight distributions

were determined by SEC performed at 25 °C in THF (flow rate 1 mL·min^{-1}), using four 5 μ-SDV columns (one guard column and three columns of 4×10^3, 3×10^5, and 2×10^6 Å). The detection was performed with an RI (DN-1000, WGE Dr. Bures) and a UV/vis detector (UV 2000; 260 nm). For calibration, linear polystyrene standards (PSS, Germany) were used.

^{1}H NMR. ^{1}H NMR spectra were recorded in $CDCl_3$ with 300 and 400 MHz Bruker Avance instruments. Monomer conversions were calculated from the NMR spectra by comparing the integrations of signals from the remaining monomers and from the formed polymers.

Fourier Transform Infrared Spectroscopy (*FT-IR*). IR spectra were measured using a Bruker spectrophotometer (IFS 66/S) equipped with a deuterated triglycerine sulfate (DTGS) detector.

MALDI-TOF Mass Spectroscopy. MALDI-TOF measurements were performed on a Bruker Reflex II (Bruker Daltonik, Bremen, Germany) in the positive ion and reflection mode using external calibration (ACTH). Dithranol was used as a matrix (10 mg/mL in THF). Matrix, ionization agent (NaI), and polymer sample were mixed in a 10:1:1 ratio. A volume of 0.3 μL of the mixed solution was applied on the target.

Results and Discussion

Synthesis and Step-Growth "Click" Coupling of Model α-Alkyne, ω-Azido Heterotelechelic Polystyrenes. As described in the Introduction, the present study relies on the step-growth polymerization of short α-alkyne, ω-azido heterotelechelic polymers. Such polymers can be simply prepared in two steps: (i) ATRP using a functionalized initiator containing an unprotected terminal alkyne and (ii) nucleophilic substitution of the bromine ATRP chain end in the presence of sodium azide.[15,24] However, it has been reported that unprotected alkyne functions may lead to side reactions in radical polymerization.[9,25] Therefore, in the present study, a TMS-protected alkyne-functionalized initiator was selected. Such a TMS protecting group can be easily cleaved after polymerization in the presence of TBAF.[18] In theory, this deprotection step can be performed directly after ATRP polymerization or after the nucleophilic substitution with NaN_3. Therefore, two sequences of reactions can be considered for preparing α-alkyne, ω-azido heterotelechelic polystyrene: ATRP, deprotection, and substitution (approach **a**) or ATRP, substitution, and deprotection (approach **b**). Herein, both approaches were evaluated with model polystyrene samples ($M_n \approx 2000$ g·mol^{-1}; $M_w/M_n \approx 1.2$).

Figure S1 of the Supporting Information shows the ^{1}H NMR spectra of a polystyrene sample in different stages of approach **a**. This sample was first synthesized by ATRP in the presence of 3-(1,1,1-trimethylsilyl)-2-propynyl 2-bromo-2-methylpropanoate. After purification and isolation, the corresponding NMR spectrum displayed characteristic signals of the initiator moiety at 0.17, 0.80 to 1.05, and 3.65 to 4.2 ppm (Figure S1A of the Supporting Information). In addition, a clear signal due to the methine proton located in the α position of the terminal bromine atom can be observed at 4.30 to 4.65 ppm.[11,23] The integration of these chain-end signals indicated a degree of bromine functionality above 95%. This well-defined polymer was subsequently reacted with TBAF to deprotect the alkyne moieties. As expected, the signal of the methyl groups of TMS vanished at 0.17 ppm, and a new signal due to the alkyne terminal proton appeared at 2.31 ppm (Figure S1B of the Supporting Information). This NMR spectrum indicates an efficient deprotection process.[18] However, the chain-end peak at 4.30 to 4.65 ppm also disappeared after TBAF treatment. This seems to indicate that the bromine chain ends have been modified during this deprotection step. In fact, two new chain-end peaks can be observed in this spectrum at 5.90 to 6.25 ppm and 3.05 ppm. The first signal is typical for a polystyrene terminal unsaturation,[11,26] whereas the latter probably corresponds to the methine proton located in the α position of this double bond. These experimental observations suggest that HBr elimination occurred in the presence of TBAF. As a consequence, bromine atoms are not available for nucleophilic substitution after this step. Indeed, after NaN_3 treatment, no significant change could be observed in the NMR spectrum (Figure S1C of the Supporting Information). Furthermore, only a weak azide signal could be observed in the FT-IR spectrum of the final polymer (data not shown). Therefore, it seems that approach **a** cannot be used to prepare α-alkyne, ω-azido heterotelechelic polystyrene.

Figure S2 of the Supporting Information shows the ^{1}H NMR spectra of a polystyrene sample in different stages of approach **b**. In this case, NaN_3 nucleophilic substitution was performed directly after the ATRP step. Both FT-IR and NMR spectroscopy evidenced the successful formation of azide chain ends. In the IR spectrum, an intense absorption band at 2094 cm^{-1}, corresponding to the asymmetric stretching vibration of the azide function, was observed. In addition, a signal due to the methine proton located in α of the azide function could be observed in the NMR spectrum (Figure S2B of the Supporting Information).[23] This peak overlaps with another signal because of the initiator moiety but can be distinguished around 4.0 ppm. Afterward, this polystyrene sample was treated with TBAF, thus leading to the removal of the TMS protecting group (Figure S2C of the Supporting Information). After purification and isolation, the final polystyrene exhibited clear NMR and IR signals corresponding to both alkyne and azide chain ends. Therefore, approach **b** is a reliable strategy for synthesizing α-alkyne, ω-azido heterotelechelic polystyrene.

Nonetheless, another reliable pathway for preparing and polymerizing heterotelechelic polystyrene was identified (approach **c**). This alternative strategy also employed the three consecutive steps of approach **a**. However, an insufficient amount of TBAF was erroneously used, thus leading to a partial deprotection of the TMS groups. In fact, ^{1}H NMR indicated that 60−70% of the TMS groups remained intact after this step. Similarly, the bromine end groups were untouched in the presence of this small amount of TBAF (i.e., no visible elimination). Therefore, this chain end could be quantitatively transformed into an azide function by substitution with NaN_3. The resulting α-TMS-alkyne, ω-azido heterotelechelic polystyrene was subsequently dissolved in THF and stirred for 24 h in the presence of copper bromide and PMDETA. Surprisingly, even though the polymers still contained TMS end groups, step-growth polymerization occurred (Table 2, entry 1). In fact, NMR measurements indicated that the remaining TMS functions were quantitatively cleaved during the step-growth process in the presence of CuBr/PMDETA. Such an in situ cleavage has been previously described in the literature.[27] Therefore, although unexpected, approach **c** is also a possible pathway for synthesizing high-molecular weight polymers by step-growth "click" coupling.

Synthesis of Heterotelechelic Polystyrenes Containing Positionable Functional Units. Well-defined functional heterotelechelic copolymers ($DP_n \approx 20$) have been synthesized. These macromolecules contain two reactive end groups and a functional *N*-substituted maleimide in the middle of their chains. First, a sequence-controlled atom transfer radical copolymerization of styrene and a functional *N*-substituted

maleimide has been conducted in the presence of 3-(1,1,1-trimethylsilyl)-2-propynyl 2-bromo-2-methylpropanoate. To control locally the incorporation of the *N*-substituted maleimides in the polymer chains, these comonomers have been added at a precise stage of the polymerizations.[8,9]

The bulk atom transfer radical polymerization of styrene was first started at 110 °C in the presence of copper(I) bromide and *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine (PMDETA). When this homopolymerization reached approximately 40−45% of styrene conversion, the maleimide comonomer was rapidly added in the reaction medium. The ^{1}H NMR kinetic analysis of the copolymerizations indicated that the maleimides are very rapidly incorporated in the growing polystyrene chains.[8] For instance, Figure 1 shows the kinetic monitoring of a model copolymerization (Table 1, entry 3) performed with *N*-benzyl maleimide (structure MI_1 in Scheme 1). In this experiment, the maleimide MI_1 was added after 102 min of polymerization, which corresponds to a styrene conversion of ∼45% (i.e., polystyrene oligomers with a DP_n of 9). After addition (41 min), NMR clearly shows that this *N*-substituted maleimide was quantitatively copolymerized with styrene (i.e., the peaks of the monomer could not be detected in this spectrum). However, during this short interval, the conversion of styrene increased only 20% (i.e., the growing chains incorporated in average four styrene monomer units during this period). These results confirm that MI_1 is incorporated in very narrow regions of the growing polymer chains. Afterward, the polymerization was continued for an additional 127 min. During this terminal phase of the reaction, styrene homopolymerization solely takes place.[9,28] At the end of the polymerization, styrene conversion was found to be 80%, thus suggesting a DP_n of ∼16 styrene units. This theoretical chain length was confirmed by the SEC analysis of the purified copolymer (Table 1, polymer **P3**), which indicated the formation of well-defined macromolecules with a controlled molecular weight (M_n = 2880 g·mol^{-1}; $M_{n\,theoretical}$ = 2234 g·mol^{-1}) and a narrow molecular-weight distribution (M_w/M_n = 1.16).

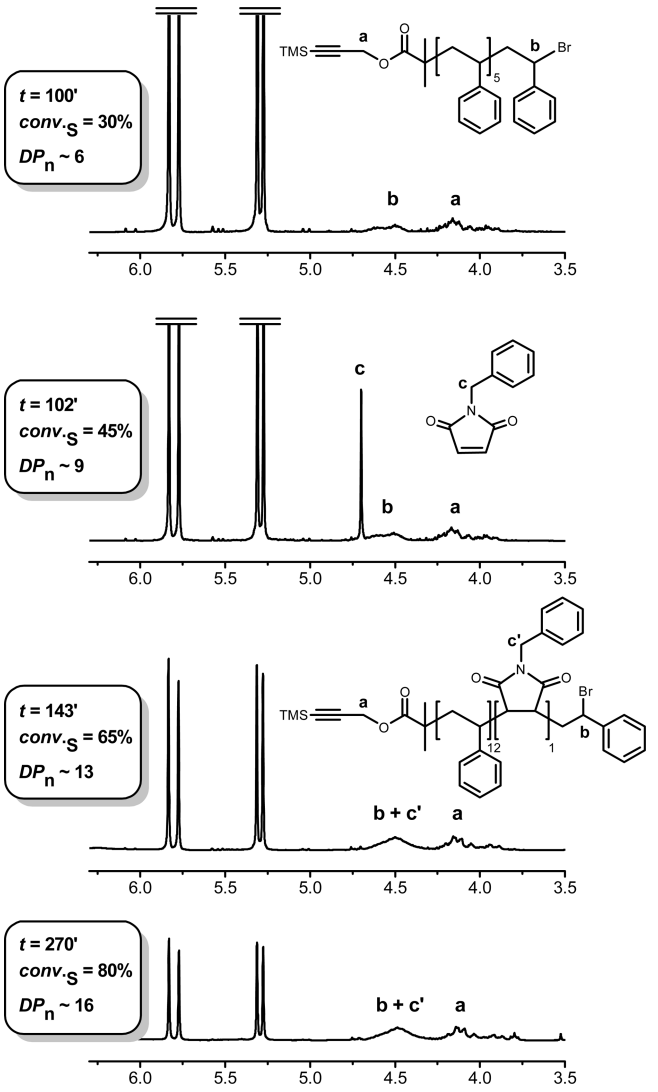


Figure 1. ^{1}H NMR spectra (zoom of the region 3.5−6.3 ppm) recorded in $CDCl_3$ in different stages of the copolymerization of styrene and MI_1 (copolymer **P3** in Table 1): (t = 100′) spectrum recorded before the addition of MI_1; (t = 102′) ^{1}H spectrum recorded shortly after the addition of MI_1; (t = 143′) spectrum recorded 41′ after the addition of MI_3, (t = 270′) spectrum recorded at the end of the copolymerization.

The NMR monitoring displayed in Figure 1 clearly shows that the maleimide MI_1 was consumed much faster than styrene. Moreover, assuming a living polymerization mechanism, one can conclude that the comonomers MI_1 have been incorporated in a short section of the polystyrene chains (i.e., approximately in the middle). However, as discussed in the Introduction, these copolymers still exhibit a sequence distribution. This comonomer distribution can be visualized by MALDI-TOF mass spectroscopy. For example, Figure 2 shows a MALDI-TOF spectrum recorded for a model copolymer of styrene and MI_1 (Table 1, Polymer **P4**). The interpretation of such complex copolymerization spectra was discussed in detail in a previous publication.[9] In brief, a single type of cationized chain is usually observed for styrene/MI_1 copolymers prepared by ATRP (see sketch in Figure 2). These chains contain an initiator moiety, a variable amount of styrene and MI_1 units, and a terminal unsaturation (i.e., no bromine chain end). The latter point should be briefly discussed because this terminal double bond could result from a HBr elimination step occurring either during the course of the ATRP or during the MALDI process.[29] Although both scenarios were described in the

Table 1. Characterization of the Copolymers P(S-*co*-MI) Prepared by ATRP[a]

	$[S]_0$ (equiv)	$[MI]_t$ (equiv)	$t_{add.}$ (min)[b]	$Conv._{S\,add.}$ (%)[c]	t_{end} (min)[d]	$Conv._S$ (%)[e]	$Conv._{MI}$ (%)[f]	M_n (g mol^{-1})[g]	M_w/M_n[g]
P1	20 equiv				200	82		3100[h]	1.11[h]
P2	20 equiv	1 equiv MI_1	102	41	185	72	99.9	1380	1.24
P3	20 equiv	1 equiv MI_1	102	45	270	80	99.9	2880	1.16
P4	20 equiv	1 equiv MI_1	99	30	290	64	99.9	2300	1.18
P5	20 equiv	1 equiv MI_2	125	36	250	91	90	2350	1.17
P6	20 equiv	1 equiv MI_3	105	46	375	90	99.9	3300	1.19

[a] Experimental conditions: Bulk; 110 °C; $[S]_0/[I]_0/[CuBr]_0/[PMDETA]$ = 20/1/0.1/0.1. The acronyms S, MI, and I stand for styrene, *N*-substituted-maleimide, and initiator, respectively. [b] At $t_{add.}$, 1 equiv of MI was added in the copolymerization medium. [c] Conversion of styrene measured by ^{1}H NMR at $t_{add.}$ [d] t_{end} denotes the final copolymerization time. [e] Conversion of styrene measured by ^{1}H NMR at the end of the copolymerization. [f] Conversion of MI measured by ^{1}H NMR at the end of the copolymerization. [g] Measured by SEC in THF. [h] Measured after TBAF treatment and azide substitution.

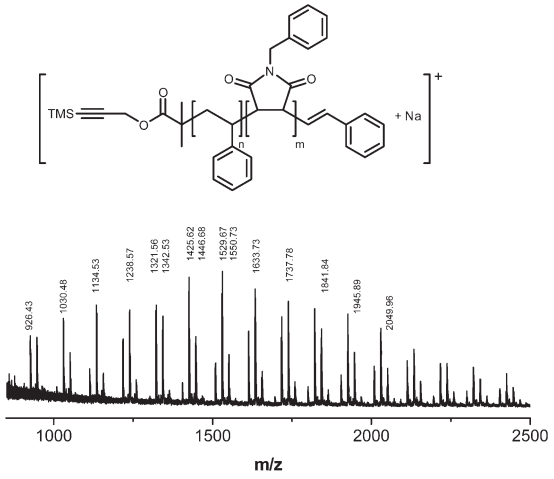


Figure 2. MALDI-TOF spectrum measured for a copolymer of styrene and MI_1 (**P4**). The spectrum was recorded from a dithranol matrix and in the presence of NaI as a cationization agent. The displayed values correspond to the main series of peaks. The scheme above the spectrum shows the probable molecular structure of the ionized copolymer chains.

literature,[10,11,30] in the present case, the elimination mostly takes place during the ionization step. Indeed, we demonstrated in a previous publication that even if the protons neighboring terminal bromine atoms can be seen in the ^{1}H NMR spectra of polystyrene samples prepared by ATRP (see Figures S1A and S2A of the Supporting Information for typical signals), the corresponding bromine atoms are usually not appearing in MALDI-TOF measurements.[9] Nevertheless, Figure 2 indicates that the comonomer sequence distribution is relatively narrow in polymer **P4**. For instance, unfunctionalized chains (i.e., homopolystyrene) and overfunctionalized chains (i.e., polymers containing three MI_1 or more) are minor components of the sequence distribution. In fact, the most intense peaks correspond to copolymer chains containing one (i.e., the desired microstructure) or two MI_1 units.

Besides the model maleimide MI_1, other functional *N*-substituted maleimide have been investigated in the present work. For instance, polystyrene chains containing periodic carboxylic acid or primary amine functions could be very relevant structures for creating 1D bioarrays. Therefore, the copolymerization of styrene with *N*-(2-(amino-*t*BOC)-ethylen)-maleimide (structure MI_2 in Scheme 1) or benzyl *N*,*N*-maleoylglycinate (structure MI_3 in Scheme 1) was studied.[31] For instance, Figure 3 shows the ^{1}H NMR kinetic monitoring of the atom transfer radical copolymerization of styrene and MI_3 (Table 1, entry 6). After 105 min of styrene homopolymerization (i.e., styrene conversion of 46%), MI_3 was added in the reaction medium. Shortly after addition, two sharp signals due to MI_3 could be observed in the NMR spectrum. However, 30 min later, these monomer signals vanished significantly (conversion of approximately 95%), thus indicating a fast maleimide copolymerization with styrene. Styrene conversion increased only 12% during this interval (i.e., approximately three styrene units per growing chain). These data lead to the same conclusions as above and clearly indicate the local consumption of MI_3. Subsequently, styrene homopolymerization was continued up to a monomer conversion of 91% (DP_n = 18). The formed copolymer (Table 1, polymer **P6**) exhibited a controlled molecular weight (M_n = 3300 g·mol^{-1}; $M_{n\,theoretical}$ = 2501 g·mol^{-1}) and a narrow molecular weight distribution (M_w/M_n = 1.19).

All copolymers prepared using ATRP (Table 1, polymers **P1**−**P6**) were subsequently transformed into reactive

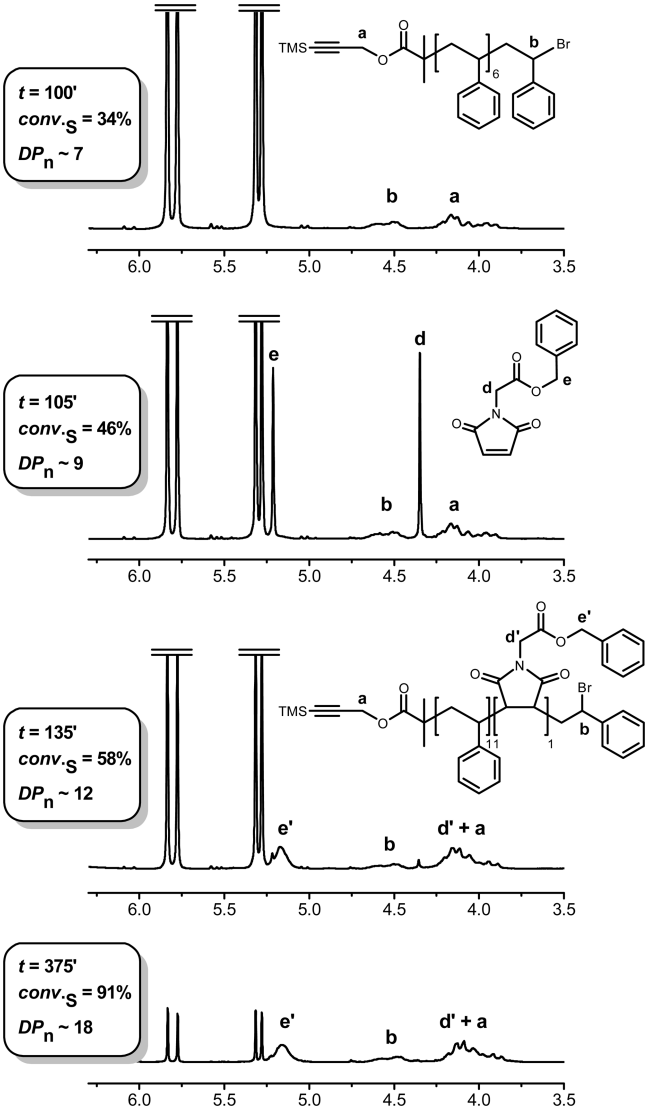


Figure 3. ^{1}H NMR spectra (zoom of the region 3.5−6.3 ppm) recorded in $CDCl_3$ in different stages of the copolymerization of styrene and MI_3 (copolymer **P6** in Table 1): (t = 100′) spectrum recorded before the addition of MI_3; (t = 105′) ^{1}H spectrum recorded shortly after the addition of MI_3; (t = 135′) spectrum recorded 30′ after the addition of MI_3, (t = 375′) spectrum recorded at the end of the copolymerization.

heterotelechelic polymers using approach **c**. This procedure led to the formation of polymers **P1′**−**P6′** (Table 2). Infrared spectroscopy analysis of the formed polymers indicated that azide end groups were formed in all cases. Indeed, an intense absorption band at 2094 cm^{-1} was observed in the IR spectrum of all copolymers (Figure 4). As aforementioned, this signal is typical for azido-functionalized polystyrene.[24] These results indicate that a large fraction of terminal bromine atoms were available for nucleophilic substitution. As described in the previous paragraph, these samples still contained a high fraction of TMS end groups.

Step-Growth "Click" Periodic Polymerization. The reactive heterotelechelic polymers were subsequently polymerized via step-growth "click" coupling. The reactive copolymers were dissolved in THF and stirred for 24 h in the presence of copper bromide and PMDETA. The formed polymers (Table 2, polymers **PP1**−**PP6**) have been characterized using ^{1}H NMR and SEC. Both methods indicated the formation of periodic copolymers.

For instance, typical NMR signals due to the formation of triazole linkages appeared in all NMR spectra (e.g., protons located in α position of the N1 of the triazole ring resonate at 4.85 to 5.25 ppm).[15,23] In addition, SEC measurements clearly evidenced the formation of high-molecular-weight periodic polymers (Table 2). Typically, after 1 day of "click" step-growth at room temperature, 5−10 reactive copolymers have been attached together. These results are in excellent agreement with those previously reported by Matyjaszewski and coworkers.[15,16] Figure 5 compares the chromatograms recorded before and after step-growth "click" coupling for the polymers **P3′** and **P6′**. In both cases, low-molecular-weight shoulders can be observed after step-growth. These small peaks may be due to some unreacted copolymers but also to the formation of cyclic macromolecules.[15,17,24,32] However, in the latter case, the overall proportion of the formed cycles would be lower than what was observed by Matyjaszewski and coworkers.[15] The analysis of the peak surface areas indicated that the low-molecular-weight shoulders represent ~10% of the overall chromatograms. This dissimilarity could be due to the differences in experimental procedures (e.g., solvent, dilution, and molecular weight of the precursors).

Table 2. Characterization of the Periodic Copolymers Prepared by Step-Growth "Click" Coupling[a]

reactive polymer	M_n (g·mol^{-1})[b]	P/CuBr/PMDETA	t (h)	M_n (g·mol^{-1})[c]	M_w/M_n[c]
P1′	3100	1/0.8/0.8	25	18600	2.98
P2′	1700	1/0.8/0.8	24	3250	2.02
P3′	2830	1/0.8/0.8	24	12200	2.40
P4′	1790	1/0.8/0.8	24	14800	2.81
P6′	2300	1/0.8/0.8	24	7950	1.98

[a] Experimental conditions: RT; in THF solution (polymer concentration in the range 60—200 mg·mL^{-1}). [b] Molecular weight of the reactive polymer before reaction. [c] Measured by SEC in THF.

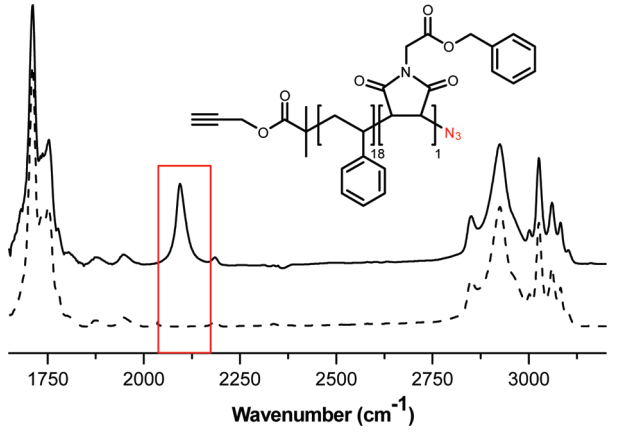


Figure 4. IR spectra (zoom of the region 1650−3200 cm^{-1}) recorded at room temperature for a copolymer of styrene and MI_3 before (dotted line) and after sodium azide treatment (**P6′**, full line). The red frame indicates the typical region for the asymmetric stretching vibration of azide functions in organic azides.[33]

Conclusions

A facile "click" step-growth strategy has been investigated for preparing functional periodic polymers. Well-defined polystyrene segments ($DP_n \approx 20$) containing functional *N*-substituted maleimides (i.e., benzyl maleimide MI_1, *N*-(2-(amino-*t*BOC)-ethylen)-maleimide MI_2, or benzyl *N*,*N*-maleoylglycinate MI_3) in the middle of their chains have been first synthesized by atom transfer radical copolymerization. The local incorporation of the maleimides in the growing polymer chains was obtained through a controlled addition process. ^{1}H NMR, SEC, and MALDI-TOF mass spectroscopy indicated the formation of well-defined copolymers with a controlled molecular weight, molecular weight distribution, and sequence distribution. Subsequently, these copolymers have been transformed into reactive heterotelechelic polymers. The formed reactive precursors were ultimately polymerized by step-growth "click" coupling in the presence of CuBr and PMDETA. SEC and ^{1}H NMR measurements evidenced that high-molecular-weight periodic copolymers were formed in all cases. Therefore, this approach appears as a straightforward method for preparing 1D molecular arrays.

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Supporting Information Available: Additional NMR figures. This material is available free of charge via the Internet at http://pubs.acs.org.

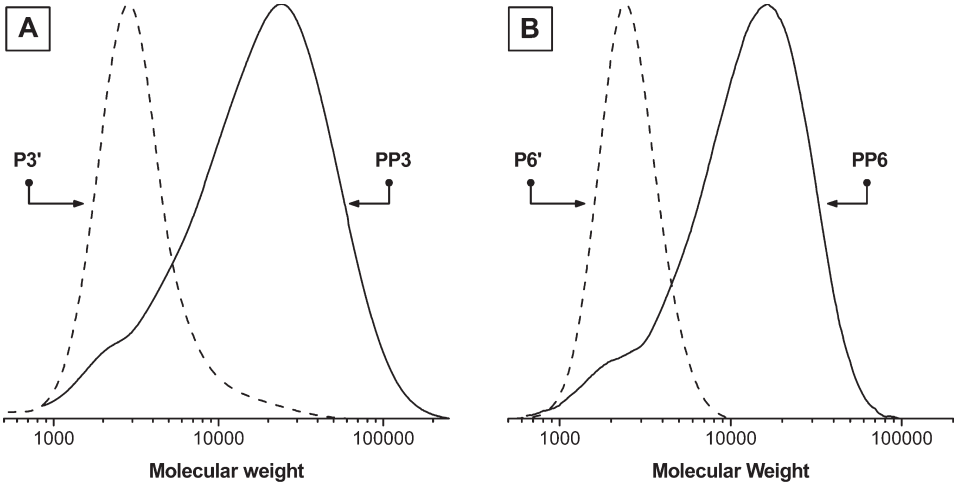

Figure 5. SEC chromatograms recorded in THF for the step-growth "click" coupling of functional heterotelechelic copolymers: (A) transformation of a heterotelechelic copolymer of styrene and MI_1 (**P3′**, dotted line) into a periodic copolymer (**PP3**, full line); (B) transformation of a heterotelechelic copolymer of styrene and MI_3 (**P6′**, dotted line) into a periodic copolymer (**PP6**, full line).

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