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ARTICLE *in* MACROMOLECULES · JUNE 2011

Impact Factor: 5.8 · DOI: 10.1021/ma200799b

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Norbornenyl-Based RAFT Agents for the Preparation of Functional Polymers via Thiol−Ene Chemistry

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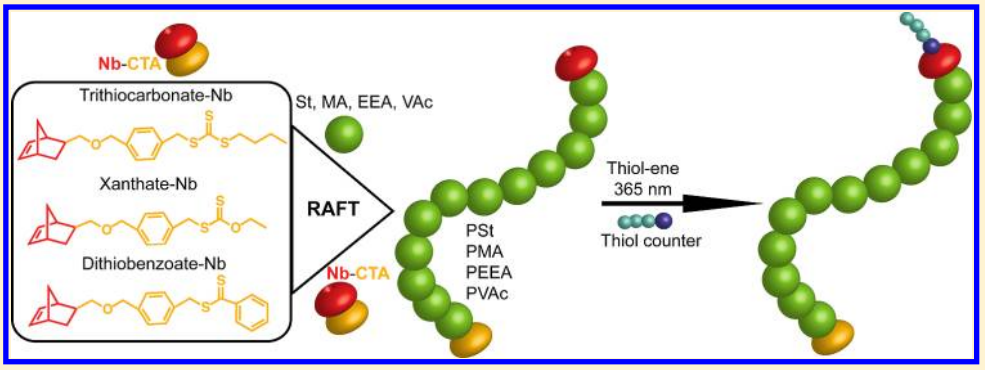
Supporting Information

ABSTRACT:



A synthetic platform for the preparation of various norbornenyl (Nb) containing reversible addition−fragmentation chain transfer (RAFT) agents has been developed. The design of the chain transfer agents (CTAs) is based on the desymmetrization of α,α′-dibromo-*p*-xylene by monosubstitution with an alkoxide anion and subsequent replacement of the residual bromine atom in the benzylic bromide to create several series of RAFT CTA including trithiocarbonate, xanthate and dithiobenzoate CTAs, allowing for the possibility to introduce other functional groups besides Nb, such as an allyl group. While a norbornene functionality was chosen as most reactive functional group toward thiols in radical-mediated thiol−ene chemistry, an allyl group was introduced for the sake of direct comparison of the double bond reactivity in the thiol−ene reaction. Control of the radical polymerization of acrylates, styrene and vinyl acetate has been achieved by using this novel family of CTAs. The results indicate that the Nb group remained intact at low monomer conversions (e.g., below 50% for styrene and vinyl acetate, below 30% for acrylates) and at optimal reaction temperatures (e.g., 70 °C for styrene and vinyl acetate, 62 and 65 °C for 1-ethoxyethyl acrylate and methyl acrylate, respectively), while the monomer-to-CTA ratio was kept high. Polymers with high end-group fidelity were modified with a series of thiol-containing compounds, leading to α-semitelechelics with different chain-end structures. While allyl-containing polymers exhibited a significantly lower reactivity, modification of the Nb-containing semitelechelics was rapid and fully accomplished under the same reaction conditions. However, for the given conditions, dodecanethiol and benzyl mercaptan showed a lower reactivity toward Nb-containing polymers, as evidenced by the obtained modification efficiency of 70% and 45%, respectively.

INTRODUCTION

The polymer community is continuously seeking for advanced materials that fulfill high demands in a range of applications. State-of-the-art methodology, as the conjunction of controlled radical polymerization techniques (CRP)[1] and postpolymerization modifications, has enabled the synthesis of telechelic polymers[2] with precisely located functional groups at the polymer chain ends. Besides the nitroxide-mediated polymerization (NMP)[3] and atom transfer radical polymerization (ATRP),[4,5] the development of the reversible addition−fragmentation chain transfer (RAFT)[6,7] controlled polymerization technique has enabled the preparation of a broad range of well-defined polymers, thanks to its exceptional versatility and its tolerance for diverse functional groups.[8,9] The RAFT process allows for the synthesis of well-defined polymers with regard to chain length and desired architecture, while maintaining a specific end group functionality that allows further postpolymerization modifications. Telechelic polymers[10] and, more specifically, semitelechelic functional polymers denote the simplest family of functional polymers, but are nevertheless essential for the fabrication of complex polymeric architectures, such as block copolymers,[11] multiblock copolymers, graft copolymers and star-shaped polymers.[12] In principle, there are two distinct routes to introduce a functional group via the chain transfer agent (CTA), either at the

Received: April 6, 2011
Revised: June 9, 2011
Published: June 22, 2011

α-chain end through the functional CTA itself,[13−17] or at the ω-chain end by chemical treatment of a trithiocarbonate RAFT agent, typically with an amine,[18,19] leading to a thiol-functional polymer. Despite unavoidable side reactions during the aminolysis,[20] we have lately utilized this route to obtain thiol terminated polymers.[21]

In this study we focus on the polymerization using specifically designed functional RAFT agents, resulting in a variety of semitelechelic polymers with unique functional groups at the α-terminus, which allow for thiol−ene reactions in a second stage. The concept of postpolymerization modification extends the range of accessible functional polymers and copolymers that are potentially applicable in both academic and industrial environment. Still, efficiency, robustness, and orthogonality, which are of paramount importance for the successful altering of physicochemical properties for further applications of these systems, may be improved. In recent years, a large number of studies has been devoted to the Huisgen Cu-catalyzed azide/alkyne click (CuAAC) reaction,[22] demonstrating the power of postpolymerization modification when combined with CRP techniques.[23−27] However, the inevitable use of the toxic copper(I) catalyst represents its major obstacle to meet strict biological requirements. In order to avoid the use of a copper catalyst, a set of alternative click strategies has been offered.[28] Mansfeld et al.[29] have recently reviewed clickable initiators, monomers and polymers, suggesting the polymer chemists what is a suitable combination of CRP and "click" approach for a desired polymeric architecture. In that context, thiol−ene reaction has emerged as an extremely powerful synthetic tool,[30,31] mainly because of its high efficiency, robustness, oxygen tolerance, and commercial availability of thiol and ene-containing compounds. The affinity of thiols toward unactivated alkenes has been known for a long time,[32] especially in the vulcanization of rubbers.[33] The radical thiol−ene step-growth polymerization mechanism was first proposed in 1938[34] and was extensively studied over the last century. Model kinetic investigations of thiol−ene photopolymerization[35,36] revealed that propagation to chain transfer ratio (k_p/k_{ct}) has a dramatic impact on the reaction kinetics and significantly depends on the nature of the ene functional group. It has been postulated that k_p and k_{ct}, and therefore the reaction rate, are correlated to the electron density of the carbon−carbon double bond and the intermediate carbon radical stability, respectively,[35] whereas the chain transfer step is shown to be the rate limiting step.[36]

It is important to note that a number of potential side reactions has to be considered, such as thiyl−thiyl radical coupling, which leads to disulfide formation, and head to head coupling of the carbon centered radicals. Those side reactions lead to limitations of the radical thiol−ene chemistry, which we reported in a previous contribution.[21] To mention the benefits, thiol−ene reactions require no transition metal catalyst and proceed with exceptionally high yields, preferably under UV light. In addition, the reaction could be thermally initiated, however with lower efficiency.[37] The thiol−ene approach seems attractive as the introduction of terminal thiol groups is straightforward[18,19] and, in some cases, the reaction could be performed in the presence of oxygen,[38] even without photoinitiator,[39,40] and even under the sunlight instead of UV light.[41] Indeed, it was Schlaad and coworkers who did initial efforts to extend the applicability of radical thiol−ene chemistry as a modular chemical tool for advanced macromolecular designs.[23,42,43] For example, Killops et al. have employed thiol−ene chemistry for the preparation of dendrimers in a solvent-free system,[44] while Schlaad and coworkers have modified poly[2-(3-butenyl)-2-oxazoline] using a thio-click approach.[45] A recent review of Hoyle and Bowman highlights both the mechanism and recent advances in applications of the radical thiol−ene reaction.[31]

In realizing the great potential of thiol−ene chemistry in combination with the RAFT process, our research has been focusing on the synthesis of α-norbornenyl functional polymers, as it has been recognized that the norbornenyl (Nb) group has the highest reactivity toward thiols in thiol−ene reaction.[30,46] There has already been growing interest in the study of norbornenyl terminated macromonomers, due to the fact that the highly ring-strained norbornene entity readily polymerizes in ring-opening metathesis polymerization (ROMP).[47,48] The unreactive character of the in-chain double bonds that are formed upon ROMP originates from the neighboring cyclopentylene rings that are preventing the acyclic double bonds of polynorbornene to participate in transfer reactions.[49] Taking advantage of these specific features, norbornene-functionalized polymers have been prepared using anionic polymerization and cationic ring-opening polymerization as exemplified by the work of Heroquez et al.[50,51] Unfortunately, these methods require strict laboratory procedures and quantitative end-group fidelity is not always assured, especially when targeting higher molecular weights. On the other hand, the pioneering studies on CRP techniques that have been done for the last decades, show clear advantages over both anionic and cationic polymerizations. However, the preparation of norbornenyl semitelechelic polymers via CRP with a high end group fidelity still remains a difficult task. For instance, Cheng et al.[52] reported on the synthesis of a norbornene-functionalized ATRP initiator for the preparation of α-norbornenyl macromonomers. When styrene (St) was used as the monomer, the polymerization was well controlled with narrow monomodal molecular weight distributions and quantitative norbornenyl end-group functionality. In contrast, the norbornene group exhibited competitive reactivity during the polymerizations of methyl acrylate (MA) and *tert*-butyl acrylate (*t*BA). Similar to this functional initiator approach, there are several contributions reporting on the synthesis of norbornenyl-functionalized RAFT agents via esterification, employing N, N′-dicyclohexylcarbodimide (DCC) and 4-*N*, *N*′-(dimethylamino)pyridine (DMAP). For example, Cheng et al.[53] prepared an *exo*-norbornene-functionalized RAFT agent by esterification of a norbornene-functionalized alcohol with an acid-functionalized RAFT agent. This compound has been used for the one-pot tandem brush synthesis by ROMP of an *exo*-norbornene functionalized RAFT agent, followed by RAFT copolymerization of styrene and maleic anhydride (MAn), mediated by a polyfunctional RAFT agent that resulted from the first reaction step. In another example, the same research group demonstrated the use of ROMP-active RAFT CTA, containing both a norbornene and a trithiocarbonate functionality, for the synthesis of poly(*tert*-butyl acrylate) (P*t*BA) to afford brush architectures via the ROMP of terminal norbornenyl groups of P*t*BA.[54] Recently, this approach was extended to heterografted amphiphilic diblock molecular brushes employing the same RAFT agent to obtain both PtBA and poly(styrene) (PS) macromonomers as precursors for the brushes.[55] In the same manner, Patton et al.[56] modified 4-cyano-4-((thiobenzoyl)sulfanyl)-pentanoic acid (CVADTB) to act as a CTA in the synthesis of α-functionalized norbornenyl, vinyl, and cinnamyl macromonomers, obtaining near-quantitative end-group fidelity. While polymerization of St and methyl methacrylate (MMA) monomers

yielded well-defined macromonomers, monomers such as MA manifested a broader polydispersity, showing a lack of inertness in the free radical polymerization process. In all cases, the necessity of suppressing the reactivity of the norbornenyl functional group during the RAFT process had to be fulfilled, therefore lower temperatures were typically applied and monomer conversions were maintained low. Finally, norbornenyl-functionalized monomers have been investigated in the preparation of multifunctional polymer architectures for their application as smart and advanced materials.[57−59]

In this work, we introduce a new family of Nb based RAFT agents, prepared in a straightforward way, for the synthesis of a wide range of norbornene-functionalized α-semitelechelics, which provides a basis upon which advanced architectures may be built, ideally via thiol−ene chemistry. The synthetic platform presented here allows for the design of diverse CTAs, and could be readily extended to other functional group of interest, in a fashion that considerably differs from literature examples given so far.[52−56,60] Another feature associated with our synthetic approach is the odor-free character of the norbornene CTAs, and their high stability under daylight and common atmospheric conditions (see Supporting Information). As the CTAs' success in mediating radical polymerization is crucial, we studied their applicability for a variety of vinyl monomers. We investigated the preparation of α-norbornene polymers with the aim to develop the most reactive thiol−ene system, consisting of thiol and norbornene functional groups. The highly reactive macromonomers can serve as potential building block precursors for the construction of functional and conjugated polymers, biopolymers and more complex advanced macromolecular materials. To demonstrate the highly reactive nature of the macromonomers, their reactivity was compared to similar allyl-containing reactive species in the thiol−ene reaction.

EXPERIMENTAL SECTION

Materials. α,α′-Dibromo-*p*-xylene (97%), carbon disulfide (≥99.9%), sodium hydride (95%), sodium 1-butanethiolate (≥95%), potassium ethyl xanthogenate (96%), 2,2′-azobis(isobutyronitrile) (AIBN), phenylmagnesium bromide (3.0 M in diethyl ether), 2,2-dimethoxy-2-phenylacetophenone (DMPA) (99%), 1-dodecanethiol (≥98%), benzyl mercaptan (99%) and 3-mercaptopropionic acid (≥99%) were purchased from Sigma-Aldrich and used as received. Vinyl acetate (VAc) (99+ %, Sigma-Aldrich) was passed through a column of basic alumina to remove the radical inhibitor. Styrene (St) (99%, extra pure, Acros Organics) was passed through a column of basic alumina to remove the radical inhibitor. 2,2′-Azobis(isobutyronitrile) (AIBN) (Sigma-Aldrich) was recrystallized twice from methanol. Allyl alcohol (>98%) was purchased from Merck and distilled prior to use. (±)-*exo*-5-Norbornene-2-methanol was synthesized following a literature procedure[61] and distilled prior to use. THF was freshly distilled over sodium/benzophenone. 1-ethoxyethyl acrylate (EEA) was prepared following the procedure of Van Camp et al.[62]

Characterization. Nuclear magnetic resonance (^{1}H- and ^{13}C NMR) spectra were recorded at 300 or 500 MHz in $CDCl_3$ solution at room temperature on a Bruker Avance 300 or Bruker DRX500 spectrometer, respectively. Chemical shifts are presented in parts per million (δ) relative to $CHCl_3$ (7.26 ppm in ^{1}H- and 77.2 ppm in ^{13}C NMR) as internal standard. Coupling constants (J) in ^{1}H NMR are given in Hz. The resonance multiplicities are described as *s* (singlet), *d* (doublet), *app t* (apparent triplet), *q* (quartet) or *m* (multiplet).

Size Exclusion Chromatography (SEC) analyses were performed on a Varian PLGPC50plus instrument, using a refractive index detector, equipped with two Plgel 5 μm MIXED-D columns 40 °C. Polystyrene standards were used for calibration and THF as eluent at a flow rate of 1 mL/min. Samples were injected using a PL AS RT autosampler.

Mass spectra were obtained by ElectroSpray Ionization (ESI−MS) using an Agilent 1100 series VL single-quad ES−MSD mass detector. Compounds 5, Nb−TTC, Nb−DTB, Nb−Xan, and Allyl−TTC tend to fragment readily upon ionization. The most characteristic peaks (m/z) were given and assigned; the relative intensities were determined, by comparing the height of the corresponding peak to the most intense (100%) peak.

Infrared spectra were obtained on a Perkin-Elmer 1600 series infrared spectrophotometer using potassium bromide (KBr) plates.

Ultraviolet (UV) light irradiation was performed with a 900 W VL 400-L UV lamp, which emits at 365 nm (intensity ca. 16 mW cm^{-2}).

Synthesis of *exo*-5-({[4-(Bromomethyl)benzyl]oxy}methyl)-bicyclo[2.2.1]hept-2-ene (4). Compound **4** (Scheme 2) was prepared by a reported procedure,[63] starting from distilled (±)-*exo*-5-norbornene-2-methanol.[61] The synthesis was repeated on 5 g scale and compound **4** was isolated after column chromatography with 53% yield. Spectroscopic data (^{1}H NMR, ^{13}C NMR, ESI−MS) of purified **4** matched the reported data.

Synthesis of 4-({[2-*exo*]-Bicyclo[2.2.1]hept-5-en-2ylmethoxy}-methyl)benzyl Butyl Carbonotrithioate (Norbornenyl-Functionalized CTA, Trithiocarbonate, Nb−TTC). A solution of benzylic bromide (**4**) (1.47 g, 4.785 mmol) in anhydrous THF (10 mL) was transferred (via cannulation) to a mixture of sodium 1-butanethiolate (805 mg, 7.177 mmol) and CS_2 (432 μL, 7.177 mmol) in anhydrous THF (15 mL). The resulting yellow mixture was stirred overnight at room temperature. The reaction was quenched with brine (100 mL) and the aqueous layer extracted with diethyl ether (3 × 150 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated *in vacuo*. The crude norbornenyl RAFT CTA (Nb−TTC) was purified by column chromatography (*n*-hexane/CH_2Cl_2: 8/2) and isolated as a yellow oil in 98% (1.846 g, 4.702 mmol) yield.

$C_{21}H_{28}OS_3$ (392.64 g/mol).

^{1}H NMR ($CDCl_3$) δ (ppm): 7.34−7.28 (*m*, 4H), 6.10 (*dd*, 1H, 5.6, 3.0 Hz), 6.05 (*dd*, 1H, 5.6, 2.8 Hz), 4.61 (*s*, 2H), 4.50 (*s*, 2H), 3.52 (*dd*, 1H, 9.2, 6.2 Hz), 3.37 (*m*, 3H), 2.79 (*m*, 2H), 1.77−1.64 (*m*, 3H), 1.43 (*m*, 2H), 1.34−1.21 (*m*, 3H), 1.11 (*app dt*, 1H, 11.6, 3.9 Hz), 0.94 (*t*, 3H, 7.3 Hz).

^{13}C NMR ($CDCl_3$) δ (ppm): 224.0, 138.6, 136.9, 136.8, 134.5, 129.5, 128.1, 75.3, 72.9, 45.2, 44.0, 41.8, 41.3, 39.1, 37.0, 30.3, 30.0, 22.3, 13.8.

ESI−MS (m/z): 393 (38%) [M + H$^+$], 269 (100%).

Synthesis of *O*-Ethyl-*S*-4-({[2-*exo*]-Bicyclo[2.2.1]hept-5-en-2ylmethoxy}methyl)benzyl Carbonodithioate (Norbornenyl-Functionalized CTA, Xanthate, Nb−Xan). A solution of benzylic bromide (**4**) (1.0 g, 3.255 mmol) in anhydrous THF (10 mL) was transferred (via cannulation) to a mixture of potassium ethyl xanthogenate (782 mg, 4.882 mmol) in anhydrous THF (15 mL). The resulting turbid mixture was stirred overnight at room temperature. The reaction was quenched with brine (100 mL) and the aqueous layer extracted with diethyl ether (3 × 150 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated *in vacuo*. The crude norbornenyl RAFT CTA (Nb−Xan) was purified by column chromatography (*n*-hexane/CH_2Cl_2 = 8/2) and isolated as a yellowish oil in quantitative yield (>99%) (1.13 g, 3.242 mmol).

$C_{19}H_{24}O_2S_2$ (348.52 g/mol).

^{1}H NMR ($CDCl_3$) δ (ppm): 7.34−7.28 (*m*, 4H), 6.10 (*dd*, 1H, 5.6, 3.0 Hz), 6.05 (*dd*, 1H, 5.6, 2.8 Hz), 4.66 (*q*, 2H, 7.1 Hz), 4.50 (*s*, 2H), 4.36 (*s*, 2H), 3.52 (*dd*, 1H, 9.2, 6.3 Hz), 3.37 (*app t*, 1H, 9.0 Hz), 2.79 (*m*, 2H), 1.72 (*m*, 1H), 1.42 (*t*, 3H, 7.1 Hz), 1.35−1.18 (*m*, 3H), 1.11 (*app dt*, 1H, 11.6, 3.9 Hz).

^{13}C NMR ($CDCl_3$) δ (ppm): 214.2, 138.4, 136.9, 136.8, 135.1, 129.3, 128.1, 75.3, 72.9, 70.2, 45.2, 44.0, 41.8, 40.4, 39.1, 30.0, 14.0.

ESI−MS (m/z): 349 (27%) [M + H$^+$], 225 (100%).

Table 1. Summary of the Optimized Reaction Conditions and Results of Polymerization of St, MA, and EEA Mediated by Nb−TTC

entry	M	$[M]_0/[CTA]_0/[AIBN]_0$	solvent, vol %	T, °C	time, h	convn,[a] %	$M_n^{exp,b}$ g/mol	PDI[b]	F. degree,[c] %
1	St	200/1/0.1	toluene, 25	60	6	16	3100	1.23	>90
2	St	200/1/0.1	toluene, 25	70	6	19	4000	1.24	>90
3	St	200/1/0.1	toluene, 25	80	6	24	4400	1.27	61
4	St	200/1/0.1	toluene, 50	70	6	16	3300	1.28	86
5	St	200/1/0.1	toluene, 25	70	4	16	3700	1.23	>90
6	St	200/1/0.1	toluene, 25	70	8	24	5200	1.24	>90
7	St	200/1/0.1	toluene, 25	70	24	40	6800	1.27	73
8	St	200/1/0.1	bulk	70	8	24	6100	1.25	>90
9	St	200/1/0.1	bulk	70	18	47	8500	1.25	>90
10	MA	400/1/0.1	toluene, 25	65	6	31	10500	1.12	86
11	MA	600/1/0.1	toluene, 25	65	12	75	34600	1.31	77
12	EEA	200/1/0.1	toluene, 25	62	12	69	15800	1.31	68

[a] Calculated from ^{1}H NMR. [b] SEC, calibrated with PS standards, THF as eluent. [c] Calculated from ^{1}H NMR and SEC.

Synthesis of 4-({[2-*exo*]-Bicyclo[2.2.1]hept-5-en-2ylmethoxy}-methyl)benzyl Dithiobenzoate (Norbornenyl-Functionalized CTA, Dithiobenzoate, Nb−DTB). A solution of benzylic bromide (**4**) (0.5 g, 1.627 mmol) in anhydrous THF (5 mL) was transferred (via cannulation) to a red solution of phenylmagnesium bromide (0.65 mL, 1.953 mmol, 3.0 M in ether) and CS_2 (117 μL, 1.953 mmol) in anhydrous THF (10 mL) at 0 °C. The resulting mixture was stirred overnight (0 °C−rt). The reaction was quenched with brine (100 mL) and the aqueous layer extracted with diethyl ether (3 × 150 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated *in vacuo*. The crude norbornenyl RAFT CTA (Nb−DTB) was purified by column chromatography (*n*-hexane/CH_2Cl_2: 95/5) and isolated as a pink oil in 90% yield (562 mg, 1.477 mmol).

$C_{23}H_{24}OS_2$ (380.57 g/mol).

^{1}H NMR ($CDCl_3$) δ (ppm): 8.00 (*m*, 2H); 7.52 (*m*, 1H), 7.40−7.31 (*m*, 6H), 6.11 (*dd*, 1H, 5.6, 3.0 Hz), 6.06 (*dd*, 1H, 5.6, 2.8 Hz), 4.60 (*s*, 2H), 4.52 (*s*, 2H), 3.52 (*dd*, 1H, 9.2, 6.2 Hz), 3.38 (*app t*, 1H, 9.0 Hz), 2.79 (*m*, 2H), 1.74 (*m*, 1H), 1.34−1.21 (*m*, 3H), 1.11 (*app dt*, 1H, 11.6, 3.9 Hz).

^{13}C NMR ($CDCl_3$) δ (ppm): 227.9, 145.0, 138.6, 136.9, 136.8, 134.4, 132.6, 129.6, 129.3, 128.2, 127.1, 75.4, 72.9, 45.2, 44.0, 42.3, 41.8, 39.1, 30.0.

ESI−MS (*m*/*z*): 663 (40%), 381 (49%) [M + H$^+$], 257 (100%).

Synthesis of 4-({Allyloxy}methyl)benzyl Bromide (5). An ice-cooled solution of freshly distilled allylalcohol (840 μL, 12.37 mmol) in anhydrous THF (50 mL) was treated with NaH (445 mg, 18.56 mmol) and stirred for 1 h at 0 °C. A solution of α,α′-dibromo-*p*-xylene (**1**, 4.0 g, 15.15 mmol) in anhydrous THF (35 mL) was added to the turbid mixture via cannulation and the resulting mixture was heated at 80 °C for 2 h. The resulting bright yellow reaction mixture was cooled to room temperature and quenched by adding a saturated aqueous NH_4Cl solution (100 mL). The layers were separated and the aqueous layer was extracted with diethyl ether (3 × 250 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated *in vacuo*. The crude benzylic bromide (**5**) was purified by column chromatography (*n*-hexane/CH_2Cl_2: 6/4) and isolated as a colorless oil in 53% (1.585 g, 6.573 mmol) yield.

$C_{11}H_{13}BrO$ (241.12 g/mol).

^{1}H NMR ($CDCl_3$) δ (ppm): 7.39−7.31 (*m*, 4H), 5.96 (*dddd*, 1H, 17.3, 10.4, 5.6, 5.5 Hz), 5.31 (*ddd*, 1H, 17.3, 3.3, 1.7 Hz), 5.21 (*ddd*, 1H, 10.4, 2.9, 1.4 Hz), 4.52 (*s*, 2H), 4.50 (*s*, 2H), 4.04 (*app dt*, 2H, 5.6, 1.4 Hz).

^{13}C NMR ($CDCl_3$) δ (ppm): 139.0, 137.3, 134.8, 129.3, 128.2, 117.4, 71.8, 71.5, 33.5.

ESI−MS (*m*/*z*): 161 (100%) [M − Br]$^+$.

Synthesis of 4-({Allyloxy}methyl)benzyl Butyl Carbonotrithioate (Allyl-Functionalized CTA, Trithiocarbonate, Allyl−TTC). A solution of the benzylic bromide (**5**) (1.0 g, 4.147 mmol) in anhydrous THF (10 mL) was transferred (via cannulation) to a mixture of sodium 1-butanethiolate (700 mg, 6.221 mmol) and CS_2 (374 μL, 6.221 mmol) in anhydrous THF (15 mL). The resulting yellow mixture is stirred for 4 h at room temperature. The reaction was quenched with brine (100 mL) and the aqueous layer extracted with diethyl ether (3 × 100 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated *in vacuo*. The crude allyl RAFT CTA (Allyl−TTC) was purified by column chromatography (*n*-hexane/CH_2Cl_2: 7/3 to 1/1) and isolated as a brown oil in 97% (1.32 g, 4.040 mmol) yield.

$C_{16}H_{22}OS_3$ (326.54 g/mol).

^{1}H NMR ($CDCl_3$) δ (ppm): 7.34−7.28 (*m*, 4H), 5.95 (*dddd*, 1H, 17.2, 10.4, 5.6, 5.5 Hz), 5.31 (*ddd*, 1H, 17.2, 3.3, 1.6 Hz), 5.21 (*ddd*, 1H, 10.4, 2.9, 1.3 Hz), 4.60 (*s*, 2H), 4.50 (*s*, 2H), 4.02 (*app dt*, 2H, 5.6, 1.4 Hz), 3.38 (*app t*, 2H, 7.4 Hz), 1.68 (*m*, 2H), 1.43 (*m*, 2H), 0.94 (*t*, 3H, 7.3 Hz).

^{13}C NMR ($CDCl_3$) δ (ppm): 224.0, 138.2, 134.9, 134.6, 129.5, 128.2, 117.4, 71.9, 71.4, 41.3, 37.0, 30.2, 22.3, 13.8.

ESI−MS (*m*/*z*): 349 (<1%) [M + Na$^+$], 327 (1%) [M + H$^+$], 269 (100%).

General Polymerization Procedures. All polymerizations were performed in a Schlenk tube and AIBN was employed as the thermal initiator. A typical polymerization procedure is as follows (Scheme 3): monomer, norbornenyl CTA, initiator, and solvent ($[M]_0/[CTA]_0/[AIBN]_0$ = 200/1/0.1) were placed in a Schlenk tube, which was degassed by three freeze−pump−thaw cycles, backfilled with nitrogen, sealed, and heated in an oil bath at the indicated temperature. The applied reaction time ranged from 2 to 48 h, depending on the targeted molecular weight and research purpose. The concentrations and reaction conditions for each specific reaction are given in Tables 1, 2 and 3. All reaction mixtures were quenched in liquid nitrogen. The polymerization kinetics using the various Nb−CTA were monitored by ^{1}H NMR and SEC. For each single reaction, at specific time intervals during the polymerization, small aliquots were withdrawn from the polymerization solution and analyzed by ^{1}H NMR spectroscopy for the determination of monomer conversions and by SEC for the determination of the molecular weights and polydispersities (PDI) of the resulting polymers. The purified polymers were obtained by repeated precipitation in 10-fold excess of corresponding nonsolvent (cold methanol for PS, 50/50 cold mixture of methanol and water for PMA/PEEA, cold hexane for PVAc). Alternatively, PEEA and PVAc were purified by removing monomer in vacuo. Polymers were collected either by decantation or filtration and dried at least overnight *in vacuo*.

General Procedure for Thiol−Ene Reaction. A typical procedure is as follows (Table 4, entry 1): Nb-containing polymer (PS, 0.08 g, 1.6×10^{-5} mol, M_n = 5000 g·mol^{-1}, PDI = 1.27) and thiol-containing compound (dodecanethiol, benzyl mercaptan or 2-mercaptopropionic acid), and 0.2 equiv of photoinitiator 2,2-dimethoxy-2-phenylacetophenone (DMPA, 0.8 mg, 3.2×10^{-6} mol) were placed in a Schlenk tube and dissolved in minimal amounts of THF (0.9 mL) required to dissolve all components. The tube was sealed and the reaction mixture was degassed with three freeze−pump−thaw cycles, backfilled with nitrogen, and placed under an irradiation source. The flask was irradiated with a 365 nm UV lamp, and was positioned at 45° toward the irradiation source, to ensure equal irradiation over the whole reacting mixture (distance between irradiation source and the flask ca. 20 cm). Irradiation time was typically 15 min except otherwise mentioned. The resulting functional polymers were precipitated three times in corresponding cold nonsolvent as stated above.

RESULTS AND DISCUSSION

In the first part of the contribution, an universal synthetic platform for the preparation of various Nb- and allyl-containing CTAs (trithiocarbonate, dithiobenzoate, and xanthate) is presented. In a second part of our research, the polymerization of a range of vinyl and acrylic monomers mediated by the new CTAs is examined. For the investigated conditions, the interference of the Nb functional group during the radical process was studied, as this strongly affects the resulting end group fidelity. In the last section, we focused on the thiol−ene modifications leading to polymers with altered chain-end structures. The major interest of the current study is to modify the Nb polymer terminus, which is expected to undergo the most efficient thiol addition.

Synthesis of the Functional Chain-Transfer Agents. The design of the Nb-containing chain transfer agents (CTAs) was based on the desymmetrization of α,α′-dibromo-*p*-xylene (**1**, Scheme 1) by monosubstitution with an alkoxide anion ($^-$OR′) and subsequent replacement of the residual bromine atom in the benzylic bromide (**2**, Scheme 1) to create the RAFT CTA (**3**, Scheme 1). The xylene moiety is the central part of the R (free radical leaving) group of the resulting CTA (**3**, Scheme 1). So far, the synthesis of norbornenyl-CTAs merely consisted of decoration of known RAFT agents. Advincula and co-workers used 4-cyano-4-((thiobenzoyl)sulfanyl)pentanoic acid (CVADTB) as a starting material for the synthesis of several double bond containing CTAs.[56] Likewise, Wooley and co-workers converted commercially available *S*-1-dodecyl-*S*′-(α,α′-dimethyl-α″-acetic acid)trithiocarbonate (DDMAT) through esterification to the desired CTA.[53] The presented approach enabled us to introduce on one hand a variety of double bond containing moieties in the R-group, and on the other hand several Z-groups, thus resulting in different types of CTAs. Indeed, the corresponding trithiocarbonate, xanthate and dithiobenzoate are readily available through a similar procedure, which emphasizes the versatility of this methodology. Using these CTAs, a wide range of monomers (e.g., styrenes, acrylates, vinylacetate, ...) can be polymerized in a controlled fashion. Moreover, the newly designed CTAs carry a double bond, which is linked through a nonhydrolyzable ether bond, in contrast to the ester linkage used by others.[53,56]

The norbornene benzylic bromide precursor (**4**, Scheme 2) was prepared by monosubstitution of α,α′-dibromo-*p*-xylene[63] (**1**, Scheme 1) with the sodium anion of (±)-*exo*-5-norbornene-2-methanol.[61] The *exo*-adduct was used as the steric hindrance

Table 2. Summary of the Optimized Reaction Conditions and Results of Polymerization of St Mediated by Nb−Dithiobenzoate and Allyl−TTC

entry[a]	CTA	time, h	convn,[b] %	$M_n^{exp,c}$ g/mol	PDI[c]	F. degree,[d] %
1	Nb−DTB	8	25	4800	1.20	>90
2	Allyl−TTC	6	19	4100	1.28	>90
3	Allyl−TTC	4	11	3000	1.29	90

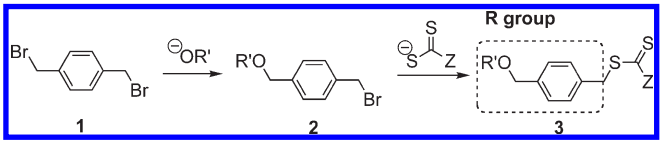
[a] Reaction conditions: $[M]_0/[CTA]_0/[AIBN]_0$ = 200/1/0.1; 25 vol % toluene; 70 °C. [b] Calculated from ^{1}H NMR. [c] SEC, calibrated with PS standards, THF as eluent. [d] Calculated from ^{1}H NMR and SEC.

Table 4. Summary of the Reaction Conditions and Results for the Thiol−Ene Post-Polymerization Modification of PS[a]

entry[b]	thiol	PS−Nb, g/mol	thiol, equiv	irradiation time, min	convn,[c] %
1	DdSH	5000	1	15	70
2	DdSH	5000	5	15	>90
3	DdSH	5000	5	10	>90
4	MPA	6000	1	15	>90
5	BSH	6000	1	15	45
6	BSH	6000	5	15	>90
entry[b]	thiol	PS−allyl, g/mol	thiol, equiv	irradiation time, min	convn,[c] %
7	DdSH	4200	1	15	20
8	MPA	4200	1	15	30
9	BSH	4200	1	15	15

[a] Abbreviations: DdSH, dodecanethiol; MPA, 2-mercaptopropionic acid; BSH, benzyl mercaptan. [b] All reactions were performed in THF as a solvent, DMPA photoinitiator, under λ = 365 nm. [c] Conversion yields percentage calculated from the disappearance of Nb peaks by ^{1}H NMR.

Scheme 1. Structural Design and General Reaction Scheme of Double-Bond-Containing RAFT CTAs[a]



[a] R′ = norbornene or other double bond containing moiety; Z = O---, S---, Ph.

Table 3. Summary of the Optimized Reaction Conditions and Results for Polymerization of VAc in Bulk, Mediated by Nb−Xan

entry	$[M]_0/[CTA]_0/[AIBN]_0$	*T*, °C	time, h	convn,[a] %	$M_n^{exp,b}$ g/mol	PDI[b]	F. degree,[c] %
1	200/1/0.5	60	26	66	17 000	1.48	<50
2	200/1/0.5	70	3.5	34	10 300	1.27	>90
3	200/1/0.5	70	4	58	17 500	1.46	<50

[a] Calculated from ^{1}H NMR. [b] SEC, calibrated with PS standards, THF as eluent. [c] Calculated from ^{1}H NMR and SEC.

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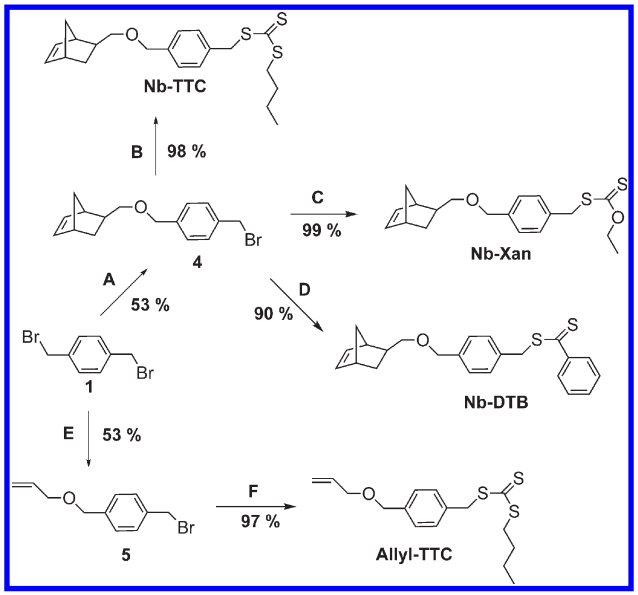
Scheme 2. Synthesis of Norbornenyl− and Allyl−RAFT CTAs[a]



[a] Reaction conditions: (A) *exo*-5-norbornene-2-methanol, NaH, THF, overnight, 80°C; (B) CS_2, sodium 1-butanethiolate, THF, overnight, room temperature; (C) potassium ethyl xanthogenate, THF, overnight, room temperature; (D) allyl alcohol, NaH, THF, 2 h, 80°C; (E) CS_2, sodium 1-butanethiolate, 4 h, room temperature. Presented yields are those of the purified compounds.

around the carbon−carbon double bond is less than in the case of the *endo*-compound,[52] enabling an easier approach of reactants during the postpolymerization modification (e.g., thiyl radicals in thiol−ene chemistry). The trithiocarbonate Nb−TTC was synthesized by overnight treatment of the precursor with an excess of CS_2 and sodium 1-butanethiolate. The choice of the Z group in CTA Nb−TTC was supported by the fact that an analogous compound, benzyl butyl trithiocarbonate, was able to mediate the controlled radical polymerization of butyl acrylate/styrene AB and ABA blocks.[64] Substitution of the benzylic bromine atom in compound **4** with the ethyl xanthogenate anion, using similar reactions conditions, provided the xanthate Nb−Xan in quantitative yield (Scheme 2). The synthesis of the corresponding dithiobenzoate Nb−DTB was more challenging as the highly reactive Grignard reagent (phenylmagnesium bromide), which is used to generate the dithiobenzoic acid salt, inhibits scaling up because of the complexity of the reaction mixture, involving side products. Therefore, we decided to perform a series of RAFT experiments with the trithiocarbonate Nb−TTC and xanthate Nb−Xan for which the synthesis scaling up (≥3 g CTA) is straightforward. The corresponding allyl-functionalized RAFT CTA, trithiocarbonate Allyl−TTC (Scheme 2), was synthesized employing the same reaction sequence, with an identical overall yield, demonstrating the versatility and reliability of the methodology, while serving in a later stage as a direct comparison of the reactivity of both Nb and allyl species toward thiols in the thiol−ene postpolymerization modification approach.

Synthesis and Characterization of the Norbornenyl (Nb) Containing Semitelechelics. *Trithiocarbonate−Nb (Nb−TTC).* The RAFT agent Nb−TTC was verified for its capabilities of mediating the homopolymerization of styrene (St), methyl acrylate (MA), and 1-ethoxyethyl acrylate (EEA), leading to semitelechelic polymers bearing a Nb group at the α terminus. EEA was chosen because the corresponding poly(1-ethoxyethyl acrylate) (PEEA) can be converted to poly(acrylic acid) (PAA) by a simple heating step at 80 °C.[62] The radical (co)polymerization reactivity of Nb species relative to St and acrylate based monomers was particularly important for the selection of appropriate reaction conditions. Theoretically, polymerization of these monomers mediated by Nb−TTC could be considered as the copolymerization of two distinct vinyl monomers (e.g., Nb based CTA and St, MA or EEA monomer, respectively), where r_1 and r_2 are the ratios of the rate constants of the different propagation reactions for any monomer pair. Therefore, the radical copolymerization reactivity ratios (r_1 and r_2) were calculated based on Alfrey and Price equations:[65]

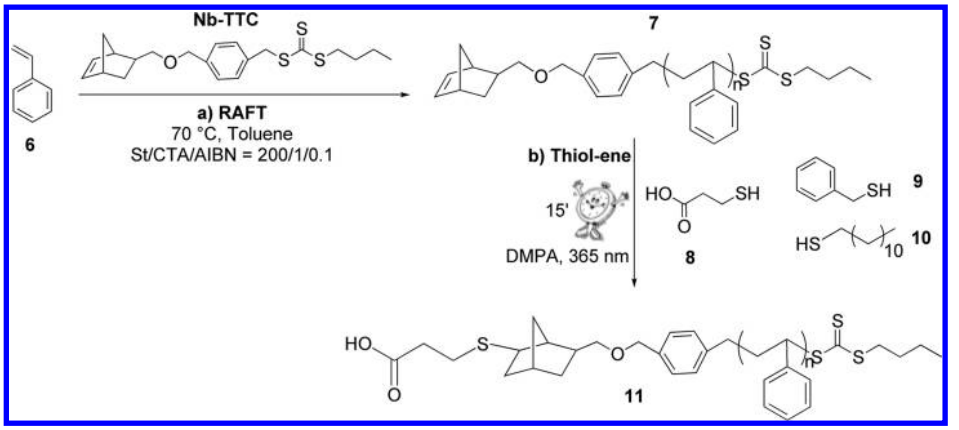
$$r_1 = (Q_1/Q_2)\, exp[-e_1(e_1 - e_2)] \quad (1)$$

$$r_2 = (Q_2/Q_1)\, exp[-e_2(e_2 - e_1)] \quad (2)$$

where Q is a measure of the reactivity, while e stands for the monomer polarity. Low homopolymerization rates for different norbornene derivatives were previously reported.[52,58,66] To estimate the reactivity of our Nb based CTAs, we employed Q and e parameters of norbornadiene ($Q = 0.051$, $e = -1.48$).[67] Taking into account Q and e values for St ($Q = 1$, $e = -0.80$), MA and its analogue EEA ($Q = 0.45$, $e = 0.64$), reactivity ratios r_1/r_2 for the Nb - St and Nb − MA/EEA pairs were 1820 and 460, respectively, indicating an extremely low tendency of the Nb group to (co)polymerize with regard to the selected monomers. In all polymerization reactions, the concentration of Nb species was maintained low, and conversions of St and acrylates were kept below 50% and 30%, respectively, to suppress side reactions with the Nb functionality during the polymerization reactions. Furthermore, we have investigated the influence of monomer-to-CTA ratio and temperature on the polymerization kinetics, ensuring that the Nb species remain intact during the entire radical polymerization process.

Table 1 summarizes the optimized reaction conditions and results of the polymerization of St, MA and EEA mediated by Nb−TTC. The effect of different reaction parameters such as temperature, dilution, monomer to CTA ratio and conversion was investigated in order to establish the optimal conditions for St homopolymerization (Scheme 3). For each specific temperature (entries 1, 2 and 3), the impact of various amounts of toluene as a solvent (e.g., bulk, 25 and 50 vol %), CTA concentrations and conversions have been investigated. The polymerization was thermally initiated employing 0.1 equiv of AIBN, following standard literature conditions. We found that the occurrence of side reactions is directly related to the temperature as the key parameter, having significant influence on the conversion. At 60 °C, St polymerization proceeded slowly (Table 1, entry 1) with the maintained high end group fidelity, as a result of the low conversion. The temperature increase up to 70 °C (Table 1, entry 2) caused an increase in the reaction rate, still with a minor end group loss that is comparable to the case of a reaction temperature of 60 °C. Further temperature increase, i.e., 80 °C, resulted in faster reaction kinetics, but also in a significant loss of the Nb end functional group. Such a temperature trend was perceived for either bulk, 25 vol % solution and 50 vol % solution conditions (Table 1, entry 4). A high end group fidelity was also retained during the bulk polymerization at 70 °C (Table 1,

Scheme 3. RAFT and Thiol−Ene Synthetic Approach toward Functional Polymers: (a) RAFT Polymerization of St Mediated by Nb−TTC; (b) Thiol−Ene Post-Polymerization Modification of Nb Containing PS



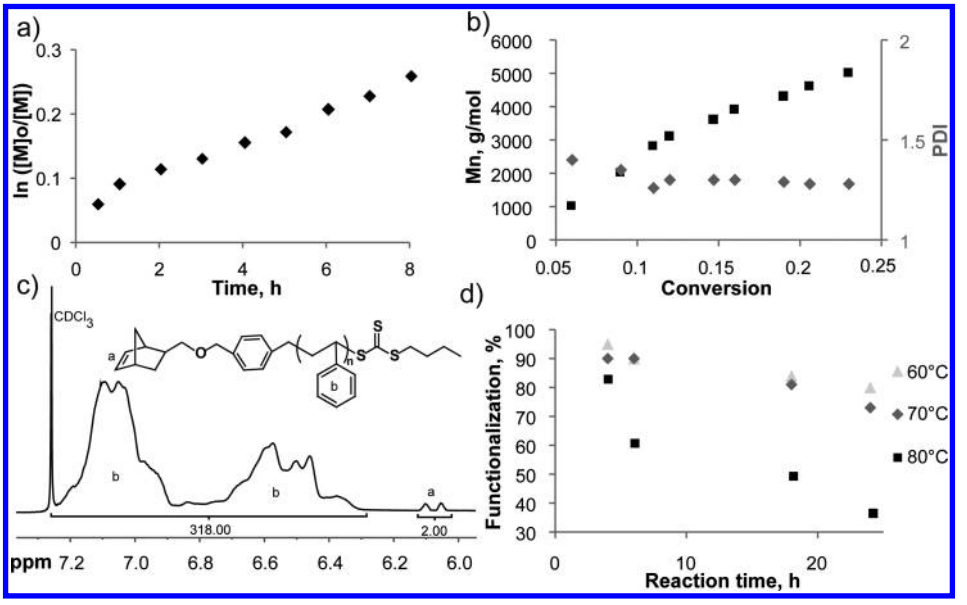


Figure 1. Polymerization of St using Nb−TTC CTA, at 70 °C, in 25 vol % toluene and with 0.1 equiv AIBN as the radical source, St/Nb−TTC = 200/1 (Table 1, entry 6): (a) first-order kinetic plot; (b) molecular weight and PDI evolution with monomer conversion; (c) detail of 500 MHz ^{1}H NMR ($CDCl_3$) of Nb-containing PS; (d) functionalization degree as a function of time for the different polymerization temperatures (see Table 1, entries 1, 2 and 3).

entries 8 and 9), despite the relatively high radical concentration. The high functionalization degree observed for bulk polymerization may be due to the relative reduction of the termination rate constants in highly viscous media (Table 1, entries 8 and 9; Figure S1, Supporting Information). Compromising between a satisfactory reaction rate and high end-group fidelity, it was found that 70 °C combined with either bulk or 25 vol % dilution are the optimal conditions for the polymerization of St.

Figure 1a shows a linear first order kinetic plot, while a steady increase of the molecular weight (MW) was observed and low polydispersity indices (PDIs) were maintained with increasing monomer conversion for entry 6, Table 1. SEC MW distributions were essentially narrow and monomodal for the investigated conversion range. The Nb functionality could be preserved to a high level of ca. 90% (Table 1, entries 1, 2, 5, 6, 8 and 9; Figure 1) under the optimal conditions. The end group functionalization was calculated combining SEC and 500 MHz ^{1}H NMR results, considering the integration ratio of the corresponding benzene ring region (6.3−7.26 ppm) and Nb doublet at 6.05 and 6.1 ppm (Figure 1c). Note that the functionalization degree will never be quantitative as the RAFT mechanism results in a certain amount of chains that will carry an AIBN adduct generated during the initiation step. A detailed ^{1}H NMR spectrum of Nb-containing PS with integration values of corresponding end-group signals is shown in Figure S2, Supporting Information.

For longer reaction times (Table 1, entry 7), a loss of Nb functionality was observed (Figure 1d). The increased PDI suggests that the Nb functionality was partially copolymerized at higher monomer conversions, given that the monomer concentration is decreasing. Under such circumstances, a variety of structures are formed along with the regular Nb-containing polymer chains. For example, termination events cause longer-chain linear polymers, while copolymerization at the Nb side results in grafted-like and branched polymers. Such nondefined structures lead to a disagreement between the experimental and the theoretical M_n values. However, a straight Mark−Houwink

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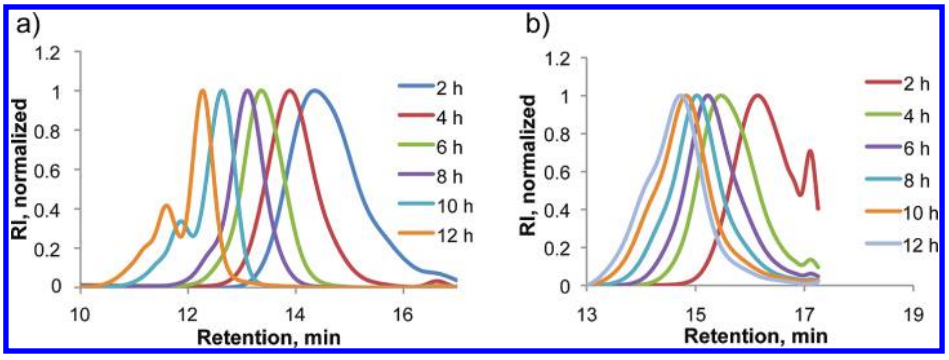

Figure 2. (a) Polymerization of MA using Nb−TTC CTA, at 65 °C, in 25 vol % toluene and with 0.1 equiv AIBN as the radical source, MA/Nb−TTC = 600/1 (Table 1, entry 11): normalized SEC chromatograms showing shoulder formation at 30% conversion or higher (corresponds to 6 h reaction time). (b) Polymerization of EEA using Nb−TTC CTA, at 62 °C, in 25 vol % toluene and with 0.1 equiv AIBN as the radical source, EEA/Nb−TTC = 200/1 (Table 1, entry 12): normalized SEC MW distribution for each aliquot recorder with the THF as eluent, showing shoulder formation at conversions higher than 40%.

plot (Figure S3, Supporting Information) revealed no presence of branched polymer species, indicating that neither transfer nor termination reactions are occurring. Both ^{1}H NMR and SEC showed that conversions higher than ca. 50% will cause side reactions, concluding that conversion is a key parameter in maintaining a high end group fidelity. Another reason for the loss of Nb function with the extended reaction time might be the transfer from the solvent, which causes radical addition to the Nb double bond, while releasing the ring strain. However, change of the solvent to dioxane resulted in a similar functionalization degree, suggesting that transfer reactions from the aromatic solvent (e.g., toluene) are not occurring and/or are not the reason for the lacking presence of Nb moiety.

In conclusion, the performed experiments show that TTC−Nb CTA is capable of mediating the polymerization of St in a well controlled manner, with preserved Nb functionality at the α terminus.

In a similar way, to demonstrate the versatility of our approach, the behavior of methyl acrylate (MA) and 1-ethoxyethyl acrylate (EEA) in the RAFT process with TTC−Nb CTA was studied. The polymerization of MA was well-controlled under the conditions highlighted in Table 1 (entries 10 and 11). For entry 10, a well-controlled reaction with a constant radical concentration was established, as shown by the linear increase of the number-average molecular weights with increasing monomer conversion (Figure S4, parts a and b, Supporting Information). ^{1}H NMR analysis revealed a high Nb content of 86% (Figure S4c, Supporting Information). Since the radical reactivity parameters of Nb and MA are not as distinct as in the case of St, copolymerization of MA and Nb species is known for many years.[68,69] In particular, Advincula et al.[56] and Wooley et al.[52] noticed that Nb containing initiation species significantly interfere during the polymerization of acrylates, at conversions higher than 30%. entry 11 (Table 1) basically confirms these statements, and, although a high initial monomer to CTA ratio of 600/1 was employed, SEC analysis (Figure 2a) clearly shows shoulders appearing at conversions higher than 30%, resulting in a dramatically reduced functionalization degree (77%). The formation of mid-chain radicals is likely to limit the end functionality to a significant extent, introducing branching over the polymer backbone, as judged by Mark−Houwink plots (Figure S5, Supporting Information). Furthermore, shoulders appearing in SEC traces with a peak molecular weights (M_p) that is twice the value of the main signal correspond to the side reactions taking place at the Nb site.

Next to MA, 1-ethoxyethyl acrylate (EEA) was polymerized using the TTC−Nb CTA. EEA was polymerized applying similar conditions as for MA (Table 1, entry 12). Many of the key features observed during the MA polymerization were also noticed in the case of EEA. Likewise, SEC analysis revealed the appearance of a shoulder at higher MW starting at ca. 40% conversion, which was attributed to the Nb interference, which leads to ill-defined structures, as discussed above in more detail (Figure 2b).

Although the evolution of the molecular weight vs conversion was linear (Figure S6, Supporting Information), lack of control was apparent from the increase in PDI values at conversions higher than 40%. In addition, obtained experimental MWs are significantly lower than theoretical MWs. Polymerization of EEA in bulk at 60 °C resulted in a noncontrolled polymerization. In contrast to the polymerization of St, bulk conditions lead to significant propagation through the Nb group. This resulted in an end group fidelity that was lower than 50% in comparison with 68% obtained in solution for PEEA, as evidenced by 500 MHz ^{1}H NMR analysis (Table 1, entry 12 and Figure S6c, Supporting Information).

Dithiobenzoate−Nb (Nb−DTB) and Trithiocarbonate−Allyl (allyl−TTC). In principle, the new synthetic CTA-platform allows the introduction of other functions of interest instead of Nb. As dithiobenzoates belong to the group of most active RAFT CTAs, we have also synthesized dithiobenzoate−Nb. Dithioester containing RAFT agents have been used for the polymerization of acrylic, methacrylic and styrenic monomers.[8] Following the optimal conditions that were found for the trithiocarboante−Nb CTA, PS was prepared at 70 °C in 25 vol % toluene, while a low monomer conversion (<30%) was targeted (Table 2, entry 1). Well-defined PS was obtained (Figure S7, TTC−), with an excellent agreement between theoretical and experimental MWs, low PDI (1.20) and essentially quantitative end group content (>90%). In accordance with our findings stated above for Nb−TTC systems, either elevated reaction temperatures or high conversions result in the loss of the Nb end group in the Nb−DTB approach.

We have also prepared allyl-terminated CTA, which could serve as a direct comparison of the reactivity of Nb and allyl species toward thiols in radical thiol−ene postmodification approach. Similarly to the approach employed for Nb functionalized CTA,

the Q and e values for the allyl group were estimated based on an equivalent compound, in this case allyl acetate. In this way, the estimated ratio of r_1/r_2 = 1940 for the St-allyl pair is even higher than for the St-Nb pair, allowing the polymerization process to be conducted with good selectivity between the two vinyl bonds. Since the reactivity parameters are similar to those of the St−Nb system, we used the optimal RAFT conditions from previous inquiries, resulting in a well-controlled polymerization process with linear increase of MW with conversion (Figure S8, Supporting Information). Polymerization reaction yielded PS with high allyl end group functionality, as depicted in Figure S8c, Supporting Information) from ^{1}H NMR interpretation. Chain transfer to polymer can take place through radical attack on the allyl double bond, which can be explained by the fact that the allyl group is unprotected, serving as the reactive center at the later stage of polymerization process when the monomer is largely consumed. Despite the relatively high PDI, no traces of higher MW population species were observed during SEC analysis, suggesting that the polymerization proceeds in a controlled way (Table 2, entries 2 and 3).

Xanthate−Nb (Nb−Xan). Macromolecular design via the interchange of xanthates (MADIX)[70] follows the same mechanism as RAFT and varies only in the choice of mediating agent, the so-called xanthate CTA. Xanthate CTAs enable the control over RAFT polymerizations of vinyl acetate (VAc), vinylpyrrolidone (NVP), and related vinyl monomers where the propagating radical is a relatively poor homolytic leaving group. Extending our synthetic platform toward Nb based CTAs, Nb−Xan was prepared (Scheme 2) and was subsequently used to mediate the polymerization of VAc. As the preparation of well-defined PVAc remains rather challenging, we have modified compound **4** (Scheme 2), in order to ensure successful polymerization of VAc. Barner-Kowollik et al.[71] studied the influence of different Z groups on the polymerization of VAc and found that Z equal to OCH_2CH_3 could lead to well-defined PVAc with PDI below 1.2.

According to our previous research,[21] the polymerization of VAc was conducted in bulk at two different temperatures (60 and 70 °C) employing different equivalents of AIBN as a thermal radical initiator, and a targeted degree of polymerization (DP) of 200. In many cases, however, we observed an induction or inhibition effect at the early stage of the polymerization, which is typical for fast propagating monomers such as VAc, and is most likely caused by the slow fragmentation of the intermediate radical. It has also been reported that impurities present in a reacting solution may cause such a behavior.[72] Moreover, increasing the CTA concentration intensified the inhibition effect.

Initial polymerization reactions were attempted with monomer to CTA ratio of 200, 0.1, and 0.2 equiv of AIBN at 60 °C but yielded no polymer (not shown in Table 3). Significant increase of AIBN up to 0.5 equiv allowed us to initiate polymerization of VAc at 60 °C with a long induction period of more than 24 h (Table 3, entry 1). In addition to the possible causes of such a behavior that were discussed above, another one could be a slow reinitiation of the leaving benzyl radical, which is slow to add to VAc and is therefore a poor choice for the R group. Hence, an elevated temperature of 70 °C was employed, as shown in Table 3, entries 2 and 3. SEC and ^{1}H NMR inspections of the reaction aliquots revealed no monomer conversion during the first 2 h of the reaction. While only 10% conversion was obtained during the third polymerization hour, rapid monomer consumption was found in the fourth reaction hour (Table 3, entries 2 and 3). Low monomer conversion (Table 3, entry 2) led to PVAc with high end group fidelity (Figure 3). However, higher monomer conversions resulted in poor functionalization degree (Table 3, entry 3).

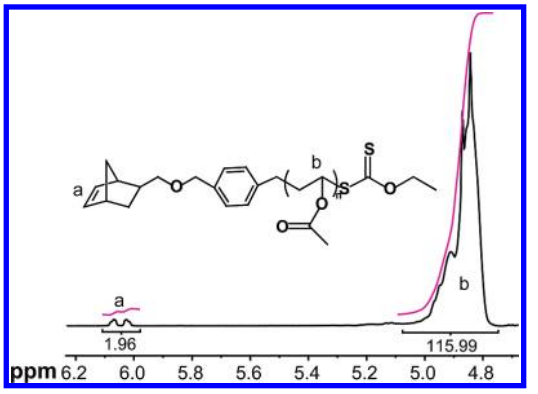

Figure 3. 500 MHz ^{1}H NMR ($CDCl_3$) spectrum detail of Nb−containing PVAc (Table 3, entry 2).

Despite the similarity of Q and e factors (VAc: Q = 0.026 and e = −0.88; norbornadiene: Q = 0.051 and e = −1.48), we demonstrated that polymerization of VAc was well controlled with Nb based xanthate CTA, under the optimized conditions. Indeed, Q and e values should be carefully taken into consideration but only as an estimation, since our reaction parameters (e.g., temperature, concentration) are different from those reported in the literature.

Thiol−Ene. We have recently demonstrated that thiol−ene chemistry, in combination with RAFT polymerization, is a powerful tool for polymer-small molecule conjugations. Thiol-containing PS was obtained via aminolysis (ω-approach), that was further modified with a range of low molecular weight ene-containing compounds. Herein, with the α approach, we prepared in a direct way a range of Nb-containing semitelechelics, available for further postpolymerization modifications via thiol−ene chemistry. To demonstrate that, PS with Nb end group functionality (**7**) was modified with three different thiol-containing low molecular weight compounds: dodecanethiol (DdSH, **10**), benzyl mercaptan (BSH, **9**) and 2-mercapto propionic acid (MPA, **8**) (Scheme 3). Reaction conditions as well as the results of the thiol−ene modification of PS are summarized in Table 4. Prior to the thiol−ene reactions, a blank reaction was performed and the stability of Nb double bond was explored under the UV light, during an extended irradiation time (i.e., 1 h), which is 2 to 4 times higher than the regular irradiation time employed in our polymer functionalization systems. The potential conversion of Nb group through self-coupling was analyzed by 500 MHz ^{1}H NMR for end group determination, and SEC for determination of the molecular weights and PDI before and after the blank reaction. Comparison of the aromatic protons (6.3−7.3 ppm) to the Nb protons (6.05 and 6.1 ppm) before and after the irradiation revealed no reaction occurring at the Nb α-terminus. The SEC chromatogram showed neither shoulder formation nor increase in PDI, with number-average molecular weight (M_n) and peak molecular weight (M_p) being identical before and after the reaction.

All postpolymerization modification reactions were performed in THF, under 365 nm, with 0.2 equiv of 2,2-dimethoxy-2-phenylacetophenone (DMPA) as photoinitiator. Initially, 1 equiv of the thiol-containing low MW compound was employed as required to address click conditions,[73] but only in the case of

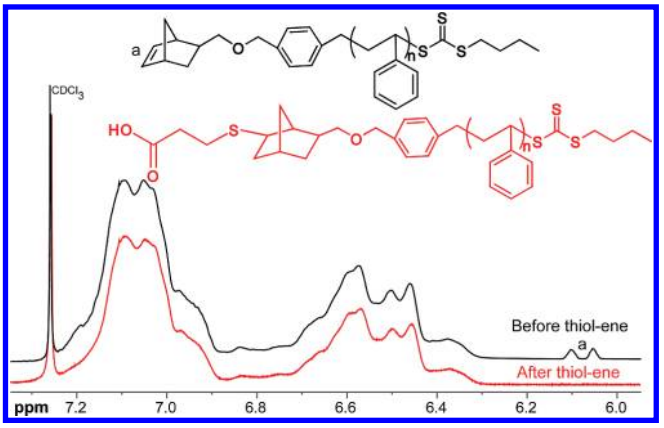

Figure 4. 500 MHz ^{1}H NMR ($CDCl_3$) for PS before (upper, Nb doublet present) and after (bottom, Nb doublet absent) thiol−ene modification (entry 4, Table 4).

2-mercaptopropionic acid (**8**, Scheme 3), an equimolar amount was sufficient to entirely saturate the Nb double bond (Table 4, entry 4), leading to successfully modified PS (**11**, Scheme 3). Unreacted thiols, if any, were removed during the precipitation of polymer in cold methanol. Figure 4 shows distinct Nb peaks decreasing toward the end of the postpolymerization modification process. Investigations with dodecanethiol (Table 4, entry 1) and benzyl mercaptan (Table 4, entry 5) revealed significantly lower functionalization efficiency of 70 and 45%, respectively. These results are consistent with the findings of Hoyle et al. that thiols based on mercaptopropionate esters copolymerize with a given ene more quickly than mercaptoacetate esters, which in turn reacts more quickly than alkyl thiols.[30] However, a 5-fold equivalent excess in case of both thiols was sufficient to reach quantitative polymer modification (Table 4, entries 2 and 6). Moreover, we have shown that a reduced reaction time (Table 4, entry 3) results in completely modified PS.

The knowledge acquired on small molecules systems[30,36,74] suggests that the Nb group is the most reactive double bond toward thiols. Cramer et al.[35,36] reported on the mechanism of radical thiol−ene chemistry and have shown that the chain transfer is the rate limiting step and that the reaction order is varying with the type of 'ene' functional group. While, for example, the thiol-allyl ether system exhibits a high propagation to chain-transfer ratio (k_p/k_{ct}), the thiol−Nb system was found to have equivalent propagation (k_p) and chain-transfer (k_{ct}) kinetic parameters, and therefore the reaction rates were of $^1/_2$ order regarding both thiol and Nb concentration.[35] The high reactivity of the Nb arises from the release of the ring strain upon the addition of the thiyl radical onto the Nb double bond.

In order to transfer aforementioned findings to the polymer systems, besides the Nb-containing PS, we have prepared allyl-containing PS (Table 2, entries 2 and 3) that serves as a direct comparison of the reactivity of both Nb and allyl functional groups. Similarly to Nb-containing PS, we have verified the self-reactivity of the allyl double bond of allyl-containing PS in typical thiol−ene reaction conditions. After 1 h of irradiation time, the allyl double bond remained present, as indicated by ^{1}H NMR. SEC analysis revealed no shoulder formation, confirming that self-coupling did not occur. In the thiol−ene reaction, under equimolar conditions, the reactivity of the allyl bond with thiols was rather limited in comparison with Nb for applied reaction conditions, e.g., 30 % conversion in the case of 2-mercaptopropionic acid (Table 4, entry 8) while only 20 and 15% when using dodecanethiol and benzyl mercaptan, respectively (Table 4, entries 7 and 9). The choice of the norbornene group is thus highly preferred over the allyl functional group for thiol−ene polymer functionalization.

CONCLUSION

We have prepared a new family of norbornenyl (Nb) based CTAs via an universal synthetic platform, which allows for the other functional groups to be incorporated as well, such as an allyl group. Polymerization of styrene, methyl acrylate, 1-ethoxyethyl acrylate and vinyl acetate was conducted in a controlled fashion, essentially retaining the Nb and the allyl end groups at the α-terminus. The optimization of the polymerization conditions revealed that low temperatures and monomer conversions (e.g., below 50% for styrene and vinyl acetate and below 30% for acrylates) are the key parameters to avoid interference of the Nb functional group with the propagating radical species. Benefits that are devoted to the unusual, ring strain promoted reactivity of the Nb group, were recognized in a rapid polymer postmodifications via radical thiol−ene reaction. The Nb functional α-semitelechelic polymers provide a basis upon which advanced architectures may be built. Further applications of the Nb-based polymers are under investigation and will be published in the near future.

ASSOCIATED CONTENT

Supporting Information. Characterization of polymerization reactions and polymers. This material is available free of charge via the Internet at http://pubs.acs.org.

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ACKNOWLEDGMENT

W.V.C. thanks the Research Foundation—Flanders (FWO) for a postdoctoral research fellowship. The authors acknowledge the Belgian Program on Interuniversity Attraction Poles initiated by the Belgian State, Prime Minister's office (Program P6/27) for financial support.

REFERENCES

(1) Braunecker, W. A.; Matyjaszewski, K. *Prog. Polym. Sci.* **2008**, *33* (1), 165–165.
(2) Tasdelen, M. A.; Kahveci, M. U.; Yagci, Y. *Prog. Polym. Sci.* **2011**, *36*, 455–567.
(3) Bosman, A. W.; Vestberg, R.; Heumann, A.; Frechet, J. M. J.; Hawker, C. J. *J. Am. Chem. Soc.* **2003**, *125* (3), 715–728.
(4) Kato, M.; Kamigaito, M.; Sawamoto, M.; Higashimura, T. *Macromolecules* **1995**, *28* (5), 1721–1723.
(5) Wang, J. S.; Matyjaszewski, K. *J. Am. Chem. Soc.* **1995**, *117* (20), 5614–5615.
(6) Chiefari, J.; Chong, Y. K.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, *31* (16), 5559–5562.
(7) Barner-Kowollik, C.; Perrier, S. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46* (17), 5715–5723.
(8) Moad, G.; Rizzardo, E.; Thang, S. H. *Polymer* **2008**, *49* (5), 1079–1131.

(9) Moad, G.; Rizzardo, E.; Thang, S. H. *Aust. J. Chem.* **2005**, *58* (6), 379–410.
(10) Jerome, R.; Henrioullegranville, M.; Boutevin, B.; Robin, J. J. *Prog. Polym. Sci.* **1991**, *16* (5), 837–906.
(11) Opsteen, J. A.; van Hest, J. C. M. *Chem. Commun.* **2005**, *1*, 57–59.
(12) Mespouille, L.; Vachaudez, M.; Suriano, F.; Gerbaux, P.; Van Camp, W.; Coulembier, O.; Degee, P.; Flammang, R.; Du Prez, F.; Dubois, P. *React. Func. Polym.* **2008**, *68* (5), 990–1003.
(13) Chen, G. J.; Tao, L.; Mantovani, G.; Ladmiral, V.; Burt, D. P.; Macpherson, J. V.; Haddleton, D. M. *Soft Matter* **2007**, *3* (6), 732–739.
(14) De, P.; Li, M.; Gondi, S. R.; Sumerlin, B. S. *J. Am. Chem. Soc.* **2008**, *130* (34), 11288–11289.
(15) Ranjan, R.; Brittain, W. J. *Macromolecules* **2007**, *40* (17), 6217–6223.
(16) Boyer, C.; Liu, J.; Bulmus, V.; Davis, T. P.; Barner-Kowollik, C.; Stenzel, M. H. *Macromolecules* **2008**, *41* (15), 5641–5650.
(17) Chen, F.; Cheng, Z. P.; Zhu, J.; Zhang, W.; Zhu, X. L. *Eur. Polym. J.* **2008**, *44* (6), 1789–1795.
(18) Patton, D. L.; Mullings, M.; Fulghum, T.; Advincula, R. C. *Macromolecules* **2005**, *38* (20), 8597–8602.
(19) Chong, Y. K.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2007**, *40* (13), 4446–4455.
(20) Lima, V.; Jiang, X. L.; Brokken-Zijp, J.; Schoenmakers, P. J.; Klumperman, B.; Van Der Linde, R. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43* (5), 959–973.
(21) Koo, S. P. S.; Stamenović, M. M.; Prasath, R. A.; Inglis, A. J.; Du Prez, F. E.; Barner-Kowollik, C.; Van Camp, W.; Junkers, T. *J. Polym. Sci., Part A: Polym. Chem.* **2010**, *48* (8), 1699–1713.
(22) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, *40* (11), 2004–2021.
(23) Lutz, J. F.; Schlaad, H. *Polymer* **2008**, *49* (4), 817–824.
(24) Lutz, J. F. *Angew. Chem., Int. Ed.* **2007**, *46* (7), 1018–1025.
(25) Angell, Y. L.; Burgess, K. *Chem. Soc. Rev.* **2007**, *36*, 1674–1689.
(26) Moses, J. E.; Moorhouse, A. D. *Chem. Soc. Rev.* **2007**, *36* (8), 1249–1262.
(27) Iha, R. K.; Wooley, K. L.; Nystrom, A. M.; Burke, D. J.; Kade, M. J.; Hawker, C. J. *Chem. Rev.* **2009**, *109* (11), 5620–5686.
(28) Becer, C. R.; Hoogenboom, R.; Schubert, U. S. *Angew. Chem., Int. Ed.* **2009**, *48* (27), 4900–4908.
(29) Mansfeld, U.; Pietsch, C.; Hoogenboom, R.; Remzi Becer, C.; Schubert, U. S. *Polym. Chem.* **2010**, *1*, 1560–1598.
(30) Hoyle, C. E.; Lee, T. Y.; Roper, T. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42* (21), 5301–5338.
(31) Hoyle, C. E.; Bowman, C. N. *Angew. Chem., Int. Ed.* **2010**, *49* (9), 1540–1573.
(32) Braun, J. v.; Murjahn, R. *Ber. Dtsch. Chem. Ges. (A and B Ser.)* **1926**, *59*, 1202–1209.
(33) Cunneen, J. I.; Shipley, F. W. *J. Polym. Sci.* **1959**, *36* (130), 77–90.
(34) Kharasch, M. S.; Read, J.; Mayo, F. R. *Chem. Ind. (London)* **1938**, *57*, 752.
(35) Cramer, N. B.; Reddy, S. K.; O'Brien, A. K.; Bowman, C. N. *Macromolecules* **2003**, *36* (21), 7964–7969.
(36) Cramer, N. B.; Davies, T.; O'Brien, A. K.; Bowman, C. N. *Macromolecules* **2003**, *36* (12), 4631–4636.
(37) Campos, L. M.; Killops, K. L.; Sakai, R.; Paulusse, J. M. J.; Damiron, D.; Drockenmuller, E.; Messmore, B. W.; Hawker, C. J. *Macromolecules* **2008**, *41* (19), 7063–7070.
(38) Kharasch, M.; Nudenberg, W.; Mantell, G. *J. Org. Chem.* **1951**, *16*, 524–532.
(39) Cramer, N. B.; Reddy, S. K.; Cole, M.; Hoyle, C.; Bowman, C. N. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42* (22), 5817–5826.
(40) Cramer, N. B.; Scott, J. P.; Bowman, C. N. *Macromolecules* **2002**, *35* (14), 5361–5365.
(41) ten Brummelhuis, N.; Diehl, C.; Schlaad, H. *Macromolecules* **2008**, *41* (24), 9946–9947.
(42) Justynska, J.; Schlaad, H. *Macromol. Rapid Commun.* **2004**, *25* (16), 1478–1481.
(43) Justynska, J.; Hordyjewicz, Z.; Schlaad, H. *Polymer* **2005**, *46* (26), 12057–12064.
(44) Killops, K. L.; Campos, L. M.; Hawker, C. J. *J. Am. Chem. Soc.* **2008**, *130* (15), 5062–5064.
(45) Gress, A.; Volkel, A.; Schlaad, H. *Macromolecules* **2007**, *40*, 7928–7933.
(46) Roper, T. M.; Guymon, C. A.; Jonsson, E. S.; Hoyle, C. E. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42* (24), 6283–6298.
(47) Rizmi, A. C. M.; Khosravi, E.; Feast, W. J.; Mohsin, M. A.; Johnson, A. F. *Polymer* **1998**, *39* (25), 6605–6610.
(48) Nomura, K.; Takahashi, S.; Imanishi, Y. *Macromolecules* **2001**, *34*, 4712–4723.
(49) Heroguez, V.; Six, J. L.; Gnanou, Y.; Fontanille, M. *Macromol. Chem. Phys.* **1998**, *199* (7), 1405–1412.
(50) Heroguez, V.; Gnanou, Y.; Fontanille, M. *Macromolecules* **1997**, *30* (17), 4791–4798.
(51) Heroguez, V.; Gnanou, Y.; Fontanille, M. *Macromol. Rapid Commun.* **1996**, *17* (2), 137–142.
(52) Cheng, C.; Khoshdel, E.; Wooley, K. L. *Macromolecules* **2005**, *38* (23), 9455–9465.
(53) Cheng, C.; Khoshdel, E.; Wooley, K. L. *Macromolecules* **2007**, *40*, 2289–2292.
(54) Li, Z.; Zhang, K.; Ma, J.; Cheng, C.; Wooley, K. L. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47* (20), 5557–5563.
(55) Li, Z.; Ma, J.; Cheng, C.; Zhang, K.; Wooley, K. L. *Macromolecules* **2010**, *43* (3), 1182–1184.
(56) Patton, D. L.; Advincula, R. C. *Macromolecules* **2006**, *39* (25), 8674–8683.
(57) Chen, L.; Hillmyer, M. A. *Macromolecules* **2009**, *42* (12), 4237–4243.
(58) Ma, J.; Cheng, C.; Wooley, K. L. *Aust. J. Chem.* **2009**, *62* (11), 1507–1519.
(59) Li, A.; Ma, J.; Wooley, K. L. *Macromolecules* **2009**, *42* (15), 5433–5436.
(60) Skey, J.; O'Reilly, R. K. *Chem. Commun.* **2008**, *35*, 4183–4185.
(61) Raimundo, J. M.; Lecomte, S.; Edelmann, M. J.; Concilio, S.; Biaggio, I.; Bosshard, C.; Gunter, P.; Diederich, F. *J. Mat. Chem.* **2004**, *14* (3), 292–295.
(62) Van Camp, W.; Du Prez, F. E.; Bon, S. A. F. *Macromolecules* **2004**, *37* (18), 6673–6675. Dervaux, B.; Van Camp, W.; Van Renterghem, L.; Du Prez, F. E. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46* (5), 1649–1661. Wouters, D.; Van Camp, W.; Dervaux, B.; Du Prez, F. E.; Schubert, U. S. *Soft Matter* **2007**, *3* (12), 1537–1541. Bernaerts, K.; Willet, N.; Van Camp, W.; Jerome, R.; Du Prez, F. *Macromolecules* **2006**, *39* (11), 3760–3769. Van Camp, W.; Hoogenboom, R.; Schubert, U. S.; Du Prez, F. E. *Macromolecules* **2005**, *38* (18), 7653–7659. Van Camp, W.; Germonpre, V.; Mespouille, L.; Dubois, P.; Goethals, E. J.; Du Prez, F. E. *React. Func. Polym.* **2007**, *67* (11), 1168–1180. Van Camp, W.; Du Prez, F. E.; Alem, H.; Demoustier-Champagne, S.; Willet, N.; Grancharov, G.; Duwez, A. S. *Eur. Polym. J.* **2010**, *46* (2), 195–201.
(63) Wigglesworth, T. J.; Teixeira, F.; Axthelm, F.; Eisler, S.; Csaba, N. S.; Merkle, H. P.; Meier, W.; Diederich, F. *Org. Biomol. Chem.* **2008**, *6* (11), 1905–1911.
(64) Bowes, A.; McLeary, J. B.; Sanderson, R. D. *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *45* (4), 588–604.
(65) Alfrey, T.; Price, C. C. *J. Polym. Sci.* **1947**, *2*, 101–106.
(66) Oishi, T.; Morioka, Y.; Fujimoto, M. *Polym. J.* **1989**, *21* (4), 287–294.
(67) Brandrup, J.; Immergut, E. H.; Grulke, E. A. *Polymer Handbook*, 4th ed.; Wiley & Sons: New York, 1999.
(68) Liu, S. S.; Sen, A. M. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42* (24), 6175–6192.
(69) Elyashiv-Barad, S.; Greinert, N.; Sen, A. *Macromolecules* **2002**, *35* (19), 7521–7526.
(70) Perrier, S.; Takolpuckdee, P. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43* (22), 5347–5393.
(71) Stenzel, M. H.; Cummins, L.; Roberts, G. E.; Davis, T. P.; Vana, P.; Barner-Kowollik, C. *Macromol. Chem. Phys.* **2003**, *204* (9), 1160–1168.
(72) Favier, A.; Barner-Kowollik, C.; Davis, T. P.; Stenzel, M. H. *Macromol. Chem. Phys.* **2004**, *205* (7), 925–936.

(73) Barner-Kowollik, C.; Du Prez, F. E.; Espeel, P.; Hawker, C. J.; Junkers, T.; Schlaad, H.; Van Camp, W. *Angew. Chem., Int. Ed.* **2010**, *50* (1), 60–62.

(74) Carioscia, J. A.; Schneidewind, L.; O'Brien, C.; Ely, R.; Feeser, C.; Cramer, N.; Bowman, C. N. *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *45* (23), 5686–5696.