Controlled copolymerization of the functional 5-membered lactone monomer, α-bromo-γ-butyrolactone, via selective organocatalysis

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A B S T R A C T
The selective nature of organic catalysts has been exploited to synthesize copolymers of the functional monomer, α-bromo-γ-butyrolactone (αBrγBL), with trimethylene carbonate (TMC), 2-allyloxymethyl-2-ethyl-trimethylene carbonate (AOMEC) and ε-caprolactone (εCL) with excellent control. The high control is attributed to high selectivity and reactivity at ambient reaction temperatures, which suppresses the degree of side reactions (e.g., transesterification) that inherently plague this class of co-monomers. In particular, good results were obtained using diphenyl phosphate (DPP) as a catalyst, resulting in copolymers with low dispersions (ĐM) (i.e., approximately 1.08) and number average molecular weights (Mn) of approximately 20,000 g/mol. The high control opened the possibility to construct more complex polymeric structures, exemplified via the synthesis of a multifunctional triblock copolymer composed of AOMEC as the center block, flanked with a statistical copolymer consisting of εCL and αBrγBL. The subsequent grafting of methyl acrylate (MA) via Cu(0)-mediated CRP on the copolymers resulted in graft copolymers with a final ĐM of less than 1.2.

1. Introduction
ROP of cyclic monomers provides a versatile route for synthesizing aliphatic polyesters and polycarbonates with high control and with a broad range of functionalities [1–6]. Among these, polyesters such as poly(ε-caprolactone) (PCL) and poly(ε-lactide) (PLLA) are of great interest due to their hydrolytic degradability, biocompatibility in many applications, industrial production and promising mechanical properties [7]. In addition, copolymerization with functional monomers enables these polymers to be precisely fine-tuned towards a specific task [8–11].

Synthesis of functional monomers is often associated with multiple steps, which limits the polymer to high cost applications. In this sense, some of the γ-lactones represent a very interesting class of building blocks. The γ-lactones exist with a plethora of different functionalities. This abundance originate from their thermodynamic propensity to ring-close, though at the same time it also renders them very hard to polymerize. Lack of homo-polymerization activity was firstly reported in the 1930s, when the polymerization of α-butyrolactone (αBL) was attempted both in presence and absence of catalyst for one year [12]. The same behavior was also observed for α-bromo-γ-butyrolactone (αBrγBL), that revealed no signs of high molar mass polymer with Sn(Oct)2 as a catalyst at 110 °C. However, this can be circumvented by using ultra-high pressure [13], extremely low reaction temperatures [14] or with the addition of cocomoners that thermodynamically favor polymerization, i.e. have a ceiling temperature (Tc) above polymerization temperature.

We have previously explored this concept through the copolymerization of αBrγBL with both εCL and LLA. The α-brominated motif can be viewed as a multifunctional handle that enables combination with many different types of chemistries, such as controlled radical polymerization (CRP). In contrast to ROP, CRP of vinyl monomers allows the synthesis of macromolecules with a diverse range of functionality, using monomers that are commercially available and readily polymerizable [15–25].

Since their advent in the mid to late 1990s, CRP [15–20] strategies have revolutionized the field, with the synthesis of a range of polymer architectures and functionality, such as blocks, stars, highly branched systems or telechelics, now possible using underlying synthetic procedures. Of these methods, single electron transfer living radical polymerization (SET-LRP) [21,22] has been shown to allow the rapid synthesis of well-defined macromolecular structures at ambient temperature. This has in turn led to a step

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change in the complexity accessible via transition metal mediated CRP, particularly in terms of structures requiring near perfect end group fidelity, such as multi-blocks and telechelics [23–25].

The ability to combine ROP- and CRP-derived structures in a single macromolecule would yield materials of great interest, in terms of compatibilizers for polymer blends, rheological control agents or emulsifiers [26,27]. Additionally, a multi-functional polymer allows specific modifications to be carried out and enables properties to be tailored to suit a particular application. This has driven the development of several monomeric structures that have dual nature, i.e. are able to both undergo ROP and act as an initiator for CRP. The most common approach is to utilize the az-halogenated motif, which will survive many ROP conditions and function as an initiator in atom transfer radical polymerization (ATRP) [27–29] and SET-LRP [21,24,30–32].

Unfortunately, our initial work on the macroinitiator formation based on 1,3-dibromobutyl-1-propion (2bryBL) resulted in poorly defined polymers with a high dispersity, which increased with prolonged reaction times. The same behavior has been observed by Nakajama et al. for the copolymerization of γ-butylrolactone and LLA [33]. This effect was believed to be twofold; firstly, from the thermodynamic features of these monomers, i.e. Tc below the polymerization temperature, and secondly, the high transesterification propensity of the catalyst.

Our previously reported synthesis utilized SnOct3 as a catalyst with a polymerization temperature of 110 °C [34]. We theorized that a reduction in temperature, along with a more selective catalyst, would result in a higher degree of control over the copolymerization behavior by bringing the polymerization temperature closer to Tc as well as suppressing the amount of transesterification. Organic compounds offer many different catalysts for ROP [35] e.g., Brønsted acids [36–44], guanidine [45–48], 4-dimethylamino-3-pyridine (DMAP) [49], and N-heterocyclic carbene (NHC)[50–53], with very different activation modes and selectivity [49,51,54–60]. In particular, diphenyl phosphate (DPP) exhibits good selectivity and high activity for δ-valerolactone (δVL) [41], C. All of the reactions were stirred at a constant temperature, which was maintained (±2 °C) using an IKAMAG® RCT basic safety control magnetic stirrer. The conversion of TMC was monitored by the change in the chemical shift at 3.0 ppm in the 1H NMR spectrum. After completion of the reaction (98% conversion, 48 h), the reaction mixture was quenched with acetic acid or triethylamine (TEA) dissolved in dichloromethane (DCM). The copolymers were subsequently dissolved in chloroform and precipitated 3–5 consecutive times in methanol. The precipitates were dried under reduced pressure.

2.2. Synthesis of 2-allyloxyethyl-2-ethyltrimethylene carbonate (AOME)

The monomer was synthesized via ring-closing depolymerization according to a previously reported protocol [63,64], along with a consecutive distillation step with the addition of acetic anhydride (0.1 eq. to AOME) and TEA (0.1 eq. to AOME) to ensure that any residual hydroxyl groups were capped.

2.3. Synthesis of macroinitiators

The reaction vessels were dried in an oven at 150 °C for 48 h prior to use. The desired amounts of the monomers (i.e., triethylene carbonate (TMC), ε-caprolactone (εCL) or 2-allyloxyethyl-2-ethyltrimethylene carbonate (AOME)) and α-bromo-γ-butyrolactone (2bryBL) (70/30 mol%) were weighed into a 50 mL two-neck round-bottom flask under a nitrogen atmosphere in a glovebox (Mbraun MB 150-GI) along with the hexanediol or benzyl alcohol initiator and 1 mol% of the catalyst (i.e., diphenyl phosphate (DPP), methanesulfonic acid (MSA), 1,5,7-triazacyclononane[4.4.0]-dec-5-ene (TBD), 1,8-diazacyclononane[5.4.0]undec-7-ene (DBU) or phosphazene base P2-Btu solution ([M]0/[I]0 = 400)). The flask was equipped with a magnetic stir bar and sealed with a two-way valve and a septum. The flask was subsequently immersed in a thermostated oil bath at 30 °C. All of the reactions were stirred at a constant temperature, which was maintained ([±2 °C] using an IKAMAG® RCT basic safety control magnetic stirrer. The conversion of TMC was monitored by the change in the chemical shift at 1.98–2.14 ppm and 4.18–4.35 ppm in the 1H NMR spectrum. After completion of the reaction (98% conversion, 48 h), the reaction mixture was quenched with acetic acid or triethylamine (TEA) dissolved in dichloromethane (DCM). The copolymers were subsequently dissolved in chloroform and precipitated 3–5 consecutive times in methanol. The precipitates were dried under reduced pressure.

2.4. Sequential synthesis of triblock macroinitiator

The reaction vessel was dried in an oven at 150 °C for 48 h prior to use. The desired amounts of the reactants (i.e., 2-allyloxyethyl-2-ethyltrimethylene carbonate (AOME), hexanediol and 5 mol% diphenyl phosphate (DPP) ([M]0/[I]0 = 50)) were weighed into a 100 mL, two-neck, round-bottom flask under a nitrogen atmosphere in a glovebox (Mbraun MB 150-GI). The flask was equipped with a magnetic stir bar and sealed with a two-way valve and a septum. The flask was subsequently immersed in a thermostated oil bath at 30 °C. Aliquots were removed, and when a monomer conversion of approximately 95% was achieved, a 50/50 mol% mixture of ε-caprolactone (εCL) and α-bromo-γ-butyrolactone was activated with concentrated hydrochloric acid for 20 min, washed with deionized water and dried prior to use.

Chloroform (HPLC grade, Fisher Scientific, Germany), methanol (general purpose grade, Fisher Scientific, Germany), acetic acid (Sigma-Aldrich, Sweden), triethylamine (TEA) (Sigma-Aldrich, Sweden), dichloromethane (DCM) (Fisher Scientific, Germany), sodium hydride (NaH) (60% dispersion in mineral oil, Sigma-Aldrich, Sweden), diethyl carbonate (99%, Sigma Aldrich, Sweden), trimethylolpropane allyl ether (98%, Sigma-Aldrich, Sweden), acetic acid (technical, Fisher Scientific, Germany), acetic anhydride (ReagentPlus®, ≥99%, Sigma-Aldrich, Sweden), methyl acrylate (MA) (Sigma-Aldrich, Sweden), 2,2,2-trifluoroethanol (TFE) (Apollo Scientific, UK), Cu(II)Br2 (Sigma-Aldrich, Sweden) and chloroform-d (99.8%, with silver foil, Cambridge Isotope Laboratories) were used as received.
(2Br\textsubscript{2}BL) was added to the flask. After completion of the reaction, the reaction mixture was quenched by adding a base (trimethylamine, TEA). The polymer was subsequently dissolved in chloroform and precipitated three consecutive times in methanol. The precipitate was dried under reduced pressure.

2.6. Grafting via controlled radical polymerization (CRP)

The ligand was prepared using an adapted procedure [65]. A formaldehyde solution (37% in water, 135.5 mL, 1.82 mol) and formic acid (160 mL, 4.08 mol) were added to a flask and cooled to 0 °C. Tris[(2-aminoethyl)amine (25 mL, 0.165 mol) was added dropwise with vigorous stirring, and the reaction mixture was refluxed overnight. The reaction mixture was adjusted to a pH of 10 with a saturated NaOH solution prior to extraction with 3 × 150 mL of CHCl\textsubscript{3}. The resulting organic phase was dried over MgSO\textsubscript{4} and concentrated to yield a yellow oil. The crude product was purified by distillation under reduced pressure (76 °C, 0.2 mbar).

Yield = 30.4 g (80%).

2.6. Grafting via controlled radical polymerization (CRP)

The macroinitiator, methyl acrylate (MA), copper wire and Cu(II) Br\textsubscript{2} were dissolved in 2,2,2-trifluoroethanol (TFE) and added to a vial equipped with a rubber septum and magnetic stir bar wrapped with activated copper wire. The reaction mixture was deoxygenated with a stream of nitrogen for 15 min prior to the addition of deoxygenated Me\textsubscript{6}TREN (t \textsubscript{0} = 0) followed by stirring at 25 °C for the indicated reaction time. The samples were removed periodically using a degassed syringe for analysis by \textsuperscript{1}H NMR and SEC.

3. Instruments

3.1. Nuclear magnetic resonance (NMR)

\textsuperscript{1}H NMR (400.13 MHz) and \textsuperscript{13}C NMR (100.62 MHz) spectra were recorded with a Bruker Avance 400 spectrometer at 298 K. For the measurements, either -10 mg (\textsuperscript{1}H NMR) or -100 mg (\textsuperscript{13}C NMR) of the polymer was dissolved in 0.8 mL of CDCl\textsubscript{3} in a sample tube that was 5 mm in diameter. The spectra were calibrated using the residual proton of the solvent signal (i.e., 7.26 ppm (\textsuperscript{1}H NMR) and 77.0 ppm (\textsuperscript{13}C NMR) for CHCl\textsubscript{3}).

3.2. Size exclusion chromatography (SEC)

The number-average molecular weight (M\textsubscript{n}) and dispersity (D\textsubscript{M}) of the polymers during and after polymerization were determined using a Verotech PL-GPC 50 Plus equipped with a PL-RI detector and two PLgel 5 μm MIXED-D columns that were 300 × 7.5 mm (Varian, Santa Clara). A PL-AS RT autosampler (Polymer Laboratories) was used to inject the samples, and chloroform was used as the mobile phase at a flow rate of 1 mL/min at 30 °C with toluene as an internal standard. The calibration was created using polystyrene standards with a narrow molecular weight distribution ranging from 160 to 371,000 g/mol.

4. Results and discussion

The ability to combine different functionalities within the same polymer chain with high polymerization control is a desirable feature within the field of polymer science. 2-Bromo-γ-butyrrolactone (2Br\textsubscript{2}BL) is of particular interest, being both functional and commercially accessible. Unfortunately, this monomer has highly unfavorable thermodynamic features that originate from its low T\textsubscript{c}, which results in poorly defined copolymers from Sn(Oct)\textsubscript{2} catalysed ROP at 110 °C [34]. However, recent advances in organocatalyzed ring-opening polymerization (ROP) have revealed high selectivity and reactivity at ambient temperatures, which may offer the possibility to circumvent the poor control.

4.1. Influence of the catalytic system

In the past 15 years organocatalytic ROP has been extensively developed and offers a powerful route to produce degradable polymers. The reactivities of the monomers differ substantially with the catalytic system employed. Therefore, the different selectivities and modes of activity provide a good starting point for refining the copolymerization behavior of 2Br\textsubscript{2}BL with c\textsubscript{CL}, TMC and 2-allyloxyethyl-2-ethyl-trimethylene carbonate (AOMEC).

Five different organocatalysts (Fig. 1) were selected to provide an overview of the various activation modes, ranging from organic bases to Brønsted acids. All of the copolymerizations with Brønsted acids produced copolymers of 2Br\textsubscript{2}BL with both TMC, c\textsubscript{CL} and AOMEC with high control, even at prolonged reaction times (1–5 days, Tables 1 and 2, entry 1–6). This result is in contrast to previous results based on the Sn(Oct)\textsubscript{2} catalytic system, where longer reaction times resulted in an increased dispersity [34]. This effect is believed to originate from the selective nature of the catalyst that suppresses the degree of transesterification reactions, as well as enabling the polymerization to be conducted at ambient temperatures. All of the basic catalyst systems lost their catalytic activity upon addition (entry 8–10). This could also be observed visually, in that the reaction mixture turned black immediately on addition of the catalyst. \textsuperscript{1}H NMR analysis revealed the formation of vinyl peaks due to elimination of bromine, hence explaining the deactivation of the catalyst.

4.2. Influence of the monomer and the copolymerization of 2Br\textsubscript{2}BL with c\textsubscript{CL} or TMC

The copolymerization of TMC and 2Br\textsubscript{2}BL (entry 2 in Table 1) using hexanediol as an initiator and DPP as a catalyst proceeded with high control, as indicated by the low dispersity. The reactions proceeded until they reached a high TMC monomer conversion, which occurred after 48 h. At this catalyst loading, the reaction time is similar to that commonly employed for the polymerization of the six-membered carbonate with DPP in the absence of the more stable comonomer [41,62,66]. The prepared copolymer of 2Br\textsubscript{2}BL and TMC exhibited an incorporation degree of approximately 6 mol % of 2Br\textsubscript{2}BL within the polymer (Tables 1 and 2 (entry 2)). The amount of 2Br\textsubscript{2}BL incorporated was determined by using the difference between the chemical shift of the z-proton of the monomer (δ\textsubscript{2Br\textsubscript{2}BL} = 4.55 ppm) and that of the resulting copolymer (δ\textsubscript{poly/(2Br\textsubscript{2}BL-c\textsubscript{CL})} = 4.48 ppm, Fig. 2 (left)). \textsuperscript{1}C NMR revealed that the architecture of the copolymer consisted of isolated 2Br\textsubscript{2}BL sites along the TMC backbone, visible through the presence of only two diad pairs (169 ppm and 154 ppm), together with the homosequence of TMC (Fig. 2 (right), see peaks a, b and c).

The polymerization kinetics of TMC and 2Br\textsubscript{2}BL catalyzed with DPP emphasized the level of control compared to that of the previous system based on Sn(Oct)\textsubscript{2} (Fig. 3) [34]. The resulting polymers exhibited low dispersities (D\textsubscript{M}) and linear evolution of M\textsubscript{n} with conversion of TMC (Fig. 3 (right)). The resulting copolymers had an M\textsubscript{n} of 27,000 g/mol and M\textsubscript{w} of 1.13 ([M]/[I] = 400). Similar control was observed for both the DPP catalyzed copolymerization of c\textsubscript{CL} and 2Br\textsubscript{2}BL ([M]/[I] = 400), which had an M\textsubscript{n} of approximately 20,000 g/mol and a low D\textsubscript{M} of 1.09 and AOMEC and 2Br\textsubscript{2}BL ([M]/[I] = 400), which had an M\textsubscript{n} of approximately 20,000 g/mol and a
Fig. 1. Organocatalysts used in the ring-opening polymerization of cyclic lactones and cyclic carbonates: (a) 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU); (b) 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD); (c) general structure of a phosphazene base; (d) Methanesulfonic acid (MSA); and (e) Diphenyl phosphate (DPP).

Table 1
Ring-opening polymerization of cyclic lactones and cyclic carbonates by changing the catalytic system. [M]$_{\text{tot}}$/[I]$_0$ = 400, [Cat] = 1 mol%, Temperature = 30 $^\circ$C, [M$_1$] = 70 mol%.

<table>
<thead>
<tr>
<th>Entry</th>
<th>[M$_1$]</th>
<th>[M$_2$]</th>
<th>Initiator</th>
<th>Catalyst</th>
<th>Reaction time [h]</th>
<th>Conversion [%]</th>
<th>Amount of $\alpha$BrγBL [mol%]$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rCL</td>
<td>$\alpha$BrγBL</td>
<td>Benzyl alcohol</td>
<td>DPP</td>
<td>24</td>
<td>99</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP</td>
<td>48</td>
<td>98</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP</td>
<td>24</td>
<td>97</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>2$^d$</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>AOMEC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>96</td>
<td>95</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>AOMEC</td>
<td>$\alpha$BrγBL + rCL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>96 + 24</td>
<td>95 + 93</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>MSA</td>
<td>40</td>
<td>98</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>TDB</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DBU</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>P2-t-Bu</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$ [Cat] = 5 mol%.

$^b$ Conversion of monomer [M$_1$].

$^d$ Temperature = 110 $^\circ$C.

Table 2
Molar mass and dispersity of the different polymerization using different organocatalysts. [M]$_{\text{tot}}$/[I]$_0$ = 400, [Cat] = 1 mol%, Temperature = 30 $^\circ$C, [M$_1$] = 70 mol%.

<table>
<thead>
<tr>
<th>Entry</th>
<th>[M$_1$]</th>
<th>[M$_2$]</th>
<th>Initiator</th>
<th>Catalyst</th>
<th>$M_n$ [g/mol]$^b$</th>
<th>$M_n$ theo [g/mol]$^c$</th>
<th>$\text{Mw}/\text{Mn}$$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rCL</td>
<td>$\alpha$BrγBL</td>
<td>Benzyl alcohol</td>
<td>DPP</td>
<td>18,800</td>
<td>28,400</td>
<td>1.09</td>
</tr>
<tr>
<td>2</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP</td>
<td>19,900</td>
<td>28,900</td>
<td>1.08</td>
</tr>
<tr>
<td>3</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>27,000</td>
<td>28,900</td>
<td>1.13</td>
</tr>
<tr>
<td>4</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>17,000</td>
<td>28,900</td>
<td>1.61</td>
</tr>
<tr>
<td>5</td>
<td>AOMEC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>40,800</td>
<td>4750 + 19,000</td>
<td>1.12</td>
</tr>
<tr>
<td>6</td>
<td>AOMEC</td>
<td>$\alpha$BrγBL + rCL</td>
<td>Hexanediol</td>
<td>DPP$^b$</td>
<td>31,200</td>
<td>28,900</td>
<td>1.12</td>
</tr>
<tr>
<td>7</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>MSA</td>
<td>19,000</td>
<td>28,900</td>
<td>1.12</td>
</tr>
<tr>
<td>8</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>TDB</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>DBU</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>TMC</td>
<td>$\alpha$BrγBL</td>
<td>Hexanediol</td>
<td>P2-t-Bu</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$ [Cat] = 5 mol%.

$^b$ Determined by SEC using narrow polystyrene standards, chloroform as eluent, and toluene as internal standard.

$^c$ Calculated from $M_n$ theo = $((n_1\times\text{con.n}_1)/(n_\text{Initiator}))\times m_1 + (n_{\alpha\text{BrγBL}}\times\text{con.n}_2)\times m_2$.

$^d$ $M_w/M_n$.

Fig. 2. Copolymerization of TMC and $\alpha$BrγBL was carried out using hexanediol as the initiator and DPP as the catalyst. Left: $^1$H NMR spectrum with peak assignments, entry 2 (Tables 1 and 2), for more detailed peak assignment see Supplementary Information Fig. S1 and Scheme S1. The amount of $\alpha$BrγBL in the final polymer was calculated to be approximately 6%. Right: $^{13}$C NMR spectrum, entry 2 (Tables 1 and 2).
low $D_M$ (1.09). For the copolymerization of TMC and $\alpha$BrgBL using MSA as the catalyst, the resulting $M_n$ of approximately 30,000 g/mol, was higher than the theoretical value with a slightly higher $D_M$ (1.12).

All polymerizations of aliphatic polyesters and aliphatic poly-carbonates unescapably lead to broadening of the $D_M$ at prolonged reaction times. In the case of $\alpha$BrgBL, when using Sn(Oct)$_2$ as catalyst, the onset of severe $D_M$ broadening was found much earlier in the copolymerization, even before 20% conversion of the high $T_c$ comonomer. By this affect, the copolymerization behavior renders it impossible to obtain more refined polymeric structures. However, the copolymerization behavior of $\alpha$BrgBL with $\varepsilon$CL, TMC and AOMEC catalyzed with DPP proceeded with such a high level of control that should enable the synthesis of more complex polymeric architectures, Fig. 3. In order to validate this, we investigated the formation of a triblock copolymer composed of AOMEC as a central block, flanked with a copolymer based on $\alpha$BrgBL and $\varepsilon$CL, Scheme 1.

4.3. Expanding the accessible macromolecular structures through sequential addition

The AOMEC central block was synthesized by DPP-catalyzed ROP ([M]/[I] = 50), using hexanediol as the difunctional initiator, with a conversion of approximately 95%, resulting in a middle block with an $M_n$ of approximately 8700 g/mol and a $D_M$ of approximately 1.10. This step was followed by subsequent addition of a 50/50 (mol%) mixture of $\varepsilon$CL and $\alpha$BrgBL ([I]$_{Tot}$/[I] = 400), resulting in a triblock polymer with an $M_n$ of 40,000 g/mol and a final $D_M$ of 1.12 (Fig. 5), with a final structure of ($\varepsilon$CL$_{52}$-co-$\alpha$BrgBL$_{4}$)-AOMEC$_{26}$-hexanediol- AOMEC$_{26}$-($\varepsilon$CL$_{52}$-co-$\alpha$BrgBL$_{4}$) (supporting information, Fig. S2). This was further confirmed by the SEC data for the chain extension (Fig. 4). Therefore, these results indicate the robustness of the copolymerization of $\alpha$BrgBL in conjunction with DPP enabling the synthesis of more complex macromolecular structures.

The triblock copolymer with a central AOMEC block flanked by blocks of $\varepsilon$CL/$\alpha$BrgBL copolymer was synthesized with high control of the block purity. $^{13}$C NMR revealed selective inclusion of $\alpha$BrgBL into the $\varepsilon$CL block, with the same set of singlets observed as for the copolymerization from hexanediol ($d(168–174$ ppm), Fig. 4) [2,34]. The absence of homosequences of $\alpha$BrgBL makes the $\alpha$-proton chemical shift dependent on the adjacent monomeric units, indicating the targeted macromolecular structure has been formed.

4.4. Grafting of degradable polymers via controlled radical polymerization (CRP)

Copolymers of $\alpha$BrgBL with $\varepsilon$CL can act as viable macroinitiators for SET-LRP, allowing the synthesis of grafted structures bearing side chains of various (meth)acrylic functionality [34]. Previously employed macroinitiators exhibited relatively high dispersity (>1.5), resulting in poorly defined grafted structures after CRP. Therefore, well-defined $\alpha$BrgBL-copolymers synthesized in this study were tested as macroinitiators for the polymerization of MA under SET-LRP conditions, Scheme 2.

SET-LRP using the poly(TMC-$r$-$\alpha$BrgBL) macroinitiator (entry 1, Table 3) proceeded rapidly and with a high degree of control,
yielding a polymer with a $M_n$ of approximately 50,000 g/mol and a $\bar{M}_n$ of 1.17 within 4 h (Fig. 6). The final structure was calculated to be TMC$_{225}$-co-(aBr$_7$BL$_{15}$-graft-MA$_{450}$) (see Fig. S3 in supporting information). However, deviation from pseudo-first order kinetics was observed early in the reaction, with the conversion reaching approximately 70%. This effect was due to the increased viscosity of the reaction mixture preventing stirring [67].

The molar mass of the final polymer was considerably lower than the theoretical value, which can be explained by the difference in the hydrodynamic volume of the non-linear structure compared to that of the linear polystyrene standards. After a prolonged reaction time of more than 2 h, a minor fraction ($<5\%$ compared to the major distribution) of an additional low molar mass peak was observed, corresponding to the theoretical grafting length ($M_n = 4300$ g/mol, Table 3). In a previous study [34], we observed a decrease in the amount of aBr$_7$BL incorporated into the polymer chain with prolonged reaction times, which was believed to be due to the low T$_c$ of aBr$_7$BL. Thus, an in situ relocation via transesterification of the five-membered lactone, aBr$_7$BL to the chain end will lead to the reformation of its monomeric structure. In the same manner, this process will produce species with the same molar mass as the grafted species under CRP conditions (Fig. 7). By reducing the amount of the ligand (i.e., Me$_6$TREN) from 2 equivalents into 0.2 equivalents, during the grafting step, the extent of this side reaction was reduced, although it was still detected.

The CRP grafting reaction proceeded with good control along with near complete initiation from the dispersed sites along the polymer backbone. The initiator efficiency was determined via the change in the chemical shift of the carbonyl carbon situated $a$ to the grafting site and characterized via $^{13}$C NMR. This analysis revealed...
that the carbonyl peak at 169 ppm, which is associated with the αBrγBL motif, disappeared after grafting (Fig. 2 (right) and Fig. 8 (right)). In addition, a slight shift in the TMC carbonyl carbon neighboring the grafting site was observed.

To test the tolerance of the polymerization procedure two groups that provide a further handle for functionalization, CRP grafting was attempted from the AOMEC triblock copolymer flanked by εCL-co-αBrγBL blocks. The polymer remained soluble after the grafting reaction, indicating little or no consumption of the alkene-functional AOMEC block by reaction with the propa-
gating radical. The final polymer exhibited an increase in Mn while maintaining a low Dm. Unfortunately, an even higher degree of low molecular species was formed the reaction (Fig. 2 in supplementary information).

5. Conclusions

Organocatalytic copolymerization of the functional monomer αBrγBL, with εCL, TMC and AOMEC resulted in copolymers with high control, as well as active and available grafting sites for post-polymerization reactions using CRP. The high control of the copolymerizations was attributed to the high selectivity and high activity of the organic catalyst DPP. At ambient reaction temperature, DPP was highly selective and copolymers with low dispersities were obtained. The versatility of the copolymerization was further

<table>
<thead>
<tr>
<th>Entry</th>
<th>Macroinitiator</th>
<th>(M_n, t = 0)</th>
<th>DP(_{\text{theo}}^a)</th>
<th>(M_n, \text{theo}^b) [g/mol]</th>
<th>(M_n, g/\text{mol}^c)</th>
<th>(D_m^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>poly(TMC-(r)-αBrγBL)</td>
<td>26,600</td>
<td>50</td>
<td>73,400</td>
<td>49,300</td>
<td>1.17</td>
</tr>
<tr>
<td>2</td>
<td>poly[AOMEC-(b)((εCL-co-αBrγBL))]</td>
<td>42,500</td>
<td>50</td>
<td>81,200</td>
<td>72,200</td>
<td>1.18</td>
</tr>
</tbody>
</table>

- Calculated per αBrγBL repeating unit.
- Calculated for graft copolymer.
- Determined by SEC using narrow polystyrene standards, chloroform as eluent, and toluene as internal standard.

Fig. 6. Graft polymerization of methyl acrylate (MA) using the poly(TMC-\(r\)-αBrγBL) macroinitiator. Left: Conversion as a function of reaction time. Right: \(M_n\) and \(D_m\) evolution as a function of conversion.

Fig. 7. SEC molar mass, 200 g/mol, \(D_m = 1.12\) and b) graft copolymer (entry 1, Table 3), with methyl acrylate (MA), [MA]:[Initiator]:[Me6TREN]:[Cu(0)]:[CuBr2] = [50]:[1]:[0.2]:[1.2]:[0.05], 73% conversion (4 h), \(M_n = 49,300 \text{ g/mol, } D_m = 1.17\).

that the carbonyl peak at 169 ppm, which is associated with the αBrγBL motif, disappeared after grafting (Fig. 2 (right) and Fig. 8 (right)). In addition, a slight shift in the TMC carbonyl carbon

Fig. 8. Grafting of methyl acrylate (MA) on the macroinitiator poly(TMC-\(r\)-αBrγBL) (entry 1, Table 3). Left: \(^1\)H NMR spectrum with peak assignments. Right: \(^{13}\)C NMR spectrum.
expanded through the construction of more complex polymeric structures via the synthesis of a multifunctional trilob copolymer composed of AOMEC as the center block, flanked by a statistical copolymer of CL and sBrBL. The subsequent grafting of MA via Cu(0)-mediated CRP of the two different copolymers resulted in graft copolymers with a final D_M of less than 1.2, together with complete initiation efficiency of the sBrBL repeating unit.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.polymer.2016.01.067.

References


