Electronic Supporting Information

Lactide-derived monomers for radical thiocarbonyl addition-ring-opening copolymerisation

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Summary

Materials and methods

The following chemicals were used as received: bleach (NaOCl, 11-15%, Alfa Aesar), DL-Lactide (99%, Alfa Aesar), deltahexalactone (99%, Sigma-Aldrich), isopropylamine (IPA, 98%, Sigma-Aldrich) hexamethyldisiloxane (HMDO, \geq 98%, Sigma-Aldrich), phosphorus pentasulfide (P₄S₁₀, 97% grade, Acros Organics), 1,1'-azobis(cyanocyclohexane) (VAZO-88, 98%, Sigma-Aldrich) and naphthalene (98%, Sigma-Aldrich). The following chemicals were purified before use: 2,2'-azobis(2-methylproprionitrile) (AIBN, 98%, Sigma-Aldrich), was recrystallized from methanol and dried under vacuum. Vinyl pivalate (VP, >99%, Sigma-Aldrich), *tert*-butyl acrylate (*t*BA, >99%, Sigma-Aldrich), styrene (St, >99%, Sigma-Aldrich) and methyl methacrylate (MMA, >99%, Sigma-Aldrich), were purified by passing through basic Al₂O₃.

The following solvents were used as received: toluene (Sigma-Aldrich, HPLC grade), diethyl ether (VWR, HPLC grade), pentane (Sigma-Aldrich, HPLC grade), cyclohexane (Sigma-Aldrich, HPLC grade), dichloromethane (Sigma-Aldrich, HPLC grade), ethyl acetate (EtOAc, Sigma-Aldrich, HPLC grade). Acetonitrile (MeCN, Acros, HPLC grade) was further dried using a solvent purifier (MBRAUN SP5).

Nuclear magnetic resonance (NMR) spectra (¹H, ¹³C) were recorded at 25 °C on a Bruker Avance 300 MHz instrument and all 2D NMR experiments were recorded at Bruker Avance 500 MHz equipped with 5 mm TCI cryoprobe. ¹H NMR spectra were recorded at 300.13 (500.13 for 2D NMR experiments) MHz is reported to \pm 0.5 Hz. The resonance multiplicities are described as s (singlet), d (doublet), t (triplet), q (quartet) or m (multiplet). ¹³C NMR spectra were recorded at 75.47 MHz (125.75 MHz for 2D). Chemical shifts δ are reported in parts per million (ppm) and are referenced to the residual solvent peak (CDCl₃: H = 7.26 ppm and C = 77.16 ppm).

Size-exclusion chromatography (SEC) analyses in THF was performed on a system composed of the set of three Shodex columns (KF-805 + KF-804 + KF-802.5). Detections were conducted using a Wyatt Optilab[®] rEX refractive index detector and a Varian ProStar 325 UV detector (dual wavelength analysis). Analyses were performed at 35°C and a flow rate of 1.0 mL min⁻¹. Poly(methyl methacrylate) (PMMA) standards (960 – 2.37 × 10⁵ g mol⁻¹) were used for calibration. All M_n , M_w and M_{peak} values as well as D were determined with PMMA standards.

Determination of conversion of monomers:

All monomer conversions were determined with naphthalene as internal standard, with signal at 7.8 ppm integrated as 1 and compared to characteristic signal of corresponding monomer.

For **TLD** as example, the formula for calculating conversion after X h of polymerization is as follows:

For TLP as call $Conversion(TLD) = 1 - \frac{\int_{4.9}^{5.1} TLD(X h)}{\int_{4.9}^{5.1} TLD(0 h)}$

Preparation of DL-thionolactide TLD and DL-dithionolactide DTLD

TLD and **DTLD** were prepared following the protocol F. Mangalum, et al. *RSC Adv.*, 2016, **6**, 74250–74253. Monomers were recrystallized thrice and resublimed to ensure reproducibility of results (see Fig S1 and S2 respectively for ¹H NMR.

TLD NMR: ¹H (CDCl₃; 300MHz) δ (ppm):5.06 (q, 1H), 4.98 (q, 1H), 1.79 (d, 3H), 1.76 (d, 3H) ¹³C (CDCl₃; 76 MHz) δ (ppm): 211.4, 167.5, 78.4, 75.1, 19.3, 15.5. **DTLD** NMR: ¹H (CDCl₃; 300MHz) δ (ppm):5.05 (q, 2H), 1.8 (d, 6H) ¹³C (CDCl₃; 76 MHz) δ (ppm): 211.2, 78.6, 19.5.

Preparation of thionodeltahexalactone (TdHL)

 P_4S_{10} (21.9 mmol), deltahexalactone (87.91 mmol) and hexamethyldisiloxane (146.31 mmol) were mixed in 90 mL of dried acetonitrile. Then the reaction mixture was stirred under argon for 15 minutes at room temperature and then refluxed for 4 hours. The dark mixture was then cooled down to 0°C and 22.5 mL of a K₂CO₃ solution (5M) were added carefully added and stirred during 30 min at 0°C. Then the product was mixed with water 200mL and extracted with ethyl acetate (3 x 100mL) and the combined organic layers were washed with water and brine. The organic solution was dried with magnesium sulfate and evaporated under reduced pressure. The product was purified by column chromatography with cyclohexane/ethyl acetate (7:3) eluent. For analytical purity TdHL was distilled in Kugelrohr apparatus (70°C at 0.1 mBar). Yield: 65%.

NMR: ¹H (CDCl₃; 300MHz) δ (ppm):1.79 (m, 2H); 1.91 (m, 4H); 3.20 (m, 2H); 4.50 (m, 2H). Spectrum shown in Fig. S1.

 ^{13}C (CDCl₃; 76 MHz) δ (ppm): 25.9; 28.51; 28.63; 46.17; 74.37; 227.47.

Polymerizations

All polymerizations are done in Carius tubes in bulk, at 100°C with 0.5 mol% of VAZO-88 initiator for 5 hours unless stated otherwise. Typical polymerization procedures are given below.

Synthesis of poly(St-co-TLD)

VAZO-88 (6 mg, 0.025 mmol), **TLD** (0.08 g, 0.5 mmol) and Styrene (0.468 g, 4.5 mmol) and naphthalene as internal standard (10 mg) were mixed. The solution was transferred into a Carius tube which was sealed under vacuum after degassing by three freeze-pump-thaw cycles. Then the tube was put in an oil bath at 100°C for 24 hours. The polymerization was stopped by rapid cooling. After opening of tube, part of the solution was immediately transferred to the NMR tube for conversion analysis. The polymer for SEC analysis was used after evaporation of residual monomer. For NMR study polymer was precipitated in the mixture of 70% MeOH/ 30% Water.

Conversion of **TLD** is 41% and St is 62%, $M_n = 5.7$ g mol⁻¹, D = 1.9.

Synthesis of poly(tBA-co-TLD)

VAZO-88 (5.3 mg, 0.022 mmol), **TLD** (0.07 g, 0.44 mmol) and *t*BA (0.504 g, 3.9 mmol) and naphthalene as internal standard (10 mg) were mixed. The solution was transferred into a Carius tube which was sealed under vacuum after degassing by three freeze-pump-thaw cycles. Then the tube was put in an oil bath at 100°C for 5 hours. The polymerization was stopped by rapid cooling. After opening of tube, part of the solution was immediately transferred to the NMR tube for conversion analysis. The polymer for SEC analysis was used after evaporation of residual monomer. Polymer was precipitated in the mixture of 70% MeOH/ 30% Water.

Conversion of **TLD** is 34% and of *t*BA is 33%, $M_n = 7.0$ kg mol⁻¹, D = 1.9.

Synthesis of poly(MMA-co-TLD)

VAZO-88 (6.1 mg, 0.025 mmol), **TLD** (0.08 g, 0.5 mmol) and MMA (0.45 g, 4.5 mmol) and naphthalene as internal standard (10 mg) were mixed. The solution was transferred into a Carius tube which was sealed under vacuum after degassing by three freeze-pump-thaw cycles. Then the tube was put in an oil bath at 100°C for 8 hours. The polymerization was stopped by rapid cooling. After opening of tube, part of the solution was immediately transferred to the NMR tube for conversion analysis. The polymer for SEC analysis was used after evaporation of residual monomer. Polymer was precipitated in the mixture of 70% MeOH/ 30% Water. Conversion of **TLD** is 20% and MMA is 49%, $M_n = 5.4$ kg mol⁻¹, D = 1.9.

Synthesis of poly(VP-co-TLD)

VAZO-88 (5.3 mg, 0.022 mmol), **TLD** (0.07 g, 0.44 mmol) and *t*BA (0.504 g, 3.9 mmol) and naphthalene as internal standard (10 mg) were mixed. The solution was transferred into a Carius tube which was sealed under vacuum after degassing by three freeze-pump-thaw cycles. Then the tube was put in an oil bath at 100°C for 16 hours. The polymerization was stopped by rapid cooling. After opening of tube, part of the solution was immediately transferred to the NMR tube for conversion analysis. The polymer for SEC analysis was used after evaporation of residual monomer.

Conversion of **TLD** is 39% and VP is 19%, $M_n = 1.0$ kg mol⁻¹, D = 1.2.

Chemical degradation

10 mg of the copolymer was dissolved in 1 mL of THF and 1 mL of NaClO 10% aqueous for bleaching or isopropylamine (IPA) for aminolysis was added. The mixture was stirred in a sealed vial for appropriate time and after degradation mixture of solvents was removed under vacuum and polymer was redissolved in THF for further analysis by SEC.







Figure S2 ¹H NMR in Chloroform-*d* of DTLD



Figure S3 ¹H NMR in Chloroform-*d* of TdHL



Figure S4 ¹H NMR 500 MHz in Chloroform-*d* of precipitated poly(St-*co*-**TLD**) from Table 1 with characteristic signals assigned (confirmed by HSQC see fig. S17, HMBC see figs. S16, S19-21 and COSY see fig. S18)



Figure S5 ¹H NMR in Chloroform-*d* of precipitated poly(VP-*co*-TLD) from table 1



Figure S6 ¹H NMR in Chloroform-*d* of precipitated poly(MMA-co-TLD) from table 1



Figure S7 ¹H NMR in Chloroform-*d* of precipitated poly(*t*BA-*co*-TLD) from table 1



Figure S8 ¹H NMR in Chloroform-d of precipitated poly(tBA-co-TdHL) from table S3, entry 5



Figure S9 ¹H NMR in Chloroform-*d* of precipitated poly(*t*BA-*co*-DTLD) Table S4 entry 1



Figure S10 ¹H NMR in Chloroform-d of precipitated poly(MMA-co-DTLD)) from table S4 entry 2

Polymerization tables

entry	comonomer	Time, h	Х _{тір} , %	X _{comonomer} , %	F _{TLD} , %	X _{total} , %
1		0.25	6.1	7.5	8.3	7.36
2		0.5	9.5	12.5	7.8	12.2
3		1	16.2	22.2	7.5	21.6
4		1.5	18.4	21.5	8.7	21.19
5	tBA	3.5	29.7	31.8	9.4	31.59
6		5	33	34	9.7	33.9
7		8	37.6	42.6	8.9	42.1
8		22	43.7	44.3	9.9	44.24
9ª		70	67	60	11	60.7
10		1	5	15	3.6	14
11	C+	2.5	12	19	6.6	18.3
12	51	8	34	40	8.6	39.4
13		24	41	62	6.8	59.9
14		1	4	22	2.0	20.2
15	MMA	3	9	36	2.7	33.3
16		8	20	49	4.3	46.1
17		0.75	7.0	9.5	7.6	9.25
18	VP	2	18.7	10.2	16.9	11.05
19		5	25.2	10.9	20.4	12.33
20	 	16	38.9	19.5	18.1	21.44

Table S1. Kinetics of copolymerization of **TLD** with different monomers. Reaction conditions: in bulk, 10 mol % feed of **TLD** with 0.5 mol. % VAZO-88 held at 100°C.

^aCopolymerization was done at 90°C for 70h, M_n = 12 kg mol⁻¹ D = 1.9

Table S2. Copolymerization *t*BA with different feed of **TLD**. Reaction conditions: in bulk with 0.5 mol. % VAZO-88 at 100°C for 5 hours

entry	f _{tld} , %	X _{tld} , %	X _{comonomer} , %	F _{tld} , %	<i>M_n</i> kg mol ⁻¹	Ð
1	20%	18	17	21	3.1	1.6
2	10%	33	34	10	7.0	1.9
3	5%	53	62	4	14.7	2.0
4	2%	71	91	1.6	48.9	2.1

Table S3. Copolymerization of **TdHL** with different monomers. Reaction conditions: in bulk, 0.5 mol. % VAZO-88 at 100°C for 5 hours

entry	comonomer	<i>f</i> _{тdнL} , %	Х _{тdнL} , %	X _{comonomer} , %	F_{тdhl}, %	<i>M_n</i> kg mol⁻¹	Ð
1	tBA	5	15	95	0.8	16.4	4.6
2	tBA	10	14.8	98	1.7	23.7	3.0
3	tBA	20	12	96	3.0	13.4	2.7
4	tBA	30	12	94.5	5.2	9.7	2.6
5	tBA	50	6	87.3	6.4	5.9	2.2



Figure S11. Evolution of total conversion over time for TLD – MMA, TLD –tBA, TLD – St, TLD – VP systems. f_{TLD} =0.1. T= 100°C, 0.5 mol% VAZO-88 initiator relative to monomers.



Figure S12. Influence of the feed composition of cyclic monomer in copolymerization of **TLD** with *t*BA and **TdHL** with *t*BA. Polymerizations are performed in bulk for 5h, at 100°C with 0.5 mol% of VAZO-88 initiator relative to monomers.



Figure S13. Linear behavior of M_n over $1/f_{thionolactone}$ indicates chain-terminating agent behavior for **TLD**-*t*BA and **TdHL**-*t*BA copolymerizations.

Degradation part, table S4-7, figure S14

M_w values are given to address the significance of high molar mass fragments

entry	conditions	<i>M_w</i> kg mol⁻¹	Ð
1	Poly(tBA-co- TLD) F _{TLD} =11%	14.2	1.7
2	Solubilised in THF + IPA for 30 days	11.6	1.4
3	Solubilised in THF + KOH/H ₂ O for 30 days	8.6	1.6
4	Solubilised in THF + bleach for 14 days	3.4	1.4

Table S4. Degradation of poly (tBA-co-TLD) samples (Table S1 entry 9) using different degrading agents

Table S5. Degradation of poly (St-co-TLD) (Table S1 entry 13) samples using different degrading agents

entry	conditions	<i>M_w</i> kg mol⁻¹	Ð
1	Poly(St <i>-co-</i> TLD) F _{TLD} = 7%	10.5	2.0
2	Solubilised in THF + IPA for 30 days	9.0	1.9
3	Solubilised in THF + bleach for 14 days	2.6	1.6

Table S6. Degradation of poly (MMA-co-TLD) (Table S1 entry 16) samples using different degrading agents

entry	conditions	<i>M_w</i> kg mol⁻¹	Ð
1	Poly(MMA- <i>co</i> - TLD) F _{TLD} = 4%	8.3	1.6
2	Solubilised in THF + IPA for 30 days	7.8	1.7
3	Solubilised in THF + bleach for 14 days	7.4	1.9

Table S7. Degradation of poly (tBA-co-DTLD) (Table 2) samples using different degrading agents

entry	conditions	<i>M_w</i> kg mol⁻¹	Ð
1	poly (<i>t</i> BA- <i>co-</i> DTLD) <i>F</i> _{DTLD} =5%	70.5	2.5
2	Solubilised in THF + IPA for 30 days	22.9	2.8
3	Solubilised in THF + bleach for 14 days	27	3.5



Figure S14 Degradation of poly(**DTLD**-co- tBA) with F_{DTLD} = 5% samples by bleach or isopropylamine (table S7).



Scheme S1. Mechanisms of degradation of thioester via oxidative hydrolysis (top) and nucleophilic substitution (bottom).



Microstructure investigation of poly(St-co-TLD) from Table 1 figures S15-19

Figure S15 ¹³C Jmod NMR Chloroform-*d* of precipitated poly(TLD-co-St) from Table 1



Figure S16 HMBC NMR Chloroform-*d* of precipitated poly(St-*co*-**TLD**) close-up correlation between quartet signal *a* at 5 ppm and thioester *C*₁ and ester *C*₂ moiety at 215 ppm and 175 ppm respectively.



Figure S17 HSQC NMR Chloroform-d of precipitated poly(St-co-TLD) from Table 1



Figure S18 ¹H/¹H COSY NMR Chloroform-*d* of precipitated poly(TLD-co-St) from Table 1



Figure S19 HMBC NMR Chloroform-*d* of precipitated poly(TLD-co-St) from Table 1



Figure S20. 95% joint confidence regions for r_{TLD}/r_{tBA} . Internal contours represent 80% and 50% joint confidence regions. Point estimates are r_{TLD} = 3.0 and r_{tBA} .= 1.4.



Figure S21 Calculated f_{TLD} vs total conversion for r_{TLD} = 3.0 and r_{tBA} .= 1.4, experimental points are shown as red circles.