Supporting Information

Sequential polymerization of ethylene oxide, ε-caprolactone and L-lactide: a one-pot metal-free route to tri- and pentablock terpolymers

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Experimental Section

Chemicals

ε-Caprolactone (CL, Alfa Aesar, 99%) was dried over calcium hydride for three days and distilled under vacuum. Tetrahydrofuran (THF, Fischer, HPLC grade) was dried successively by sodium and *n*-butyllithium. All other chemicals were purchased from Aldrich. *t*-BuP$_2$ (2.0 M in THF) and acetic acid (AcOH) were used as received. 3-Phenyl-1-propanol (PPA, 98%) was dried over calcium hydride and distilled under vacuum before use. Ethylene oxide (EO, 99.5%) was dried successively by calcium hydride and *n*-butyllithium prior to use. L-Lactide (LLA, 98%) was dissolved in purified THF, dried by azeotropic distillation of THF three times, and finally dissolved in purified THF making a 0.2 g mL^{-1} solution.

Instrumentation

Size exclusion chromatography (SEC) with simultaneous UV and RI detection was conducted in THF at 35 °C using two 7.8 mm × 300 mm (5 μm) Styragel columns (Styragel HR 2 and Styragel HR 4) at a flow rate of 1.0 mL min^{-1}. Calibration was done with a series of poly(ethylene oxide) (PEO) standards to obtain accurate number-average molecular weight ($M_{n,SEC}$) of the PEO block and dispersities (M_w/M_n). Nuclear magnetic resonance (NMR) measurements were carried out at room temperature using a Bruker AVANCEDIII 600 spectrometer operating at 600 MHz; $CDCl_3$ (Aldrich) was used as solvent. Integrals of the characteristic signals together with $M_{n,SEC}$ of the PEO block were used to calculate the molecular weight ($M_{n,NMR}$) of other components in the copolymers and terpolymers as well as their total molecular weights. Matrix assisted laser desorption/ionization time of flight mass spectrometry (MALDI-TOF MS) measurements were performed on a Bruker Ultraflex III MALDI-TOF mass spectrometer (Bruker Daltonik, Bremen, Germany). Samples were dissolved in THF (10 mg mL^{-1}) and mixed with a solution of potassium or sodium trifluoroacetate in THF (10 mg mL^{-1}) in a volume ratio of 5:1. This solution was then mixed with a solution of matrix, 2,5-dihdroxybenzoic acid in THF (20 mg mL^{-1}), in a volume ratio of 1:10. Then, 0.4 μL of the final solution was spotted on the target plate (dried-droplet method). The reflective positive ion mode was used to acquire the mass spectra of the samples. The calibration was done externally with the poly(methyl methacrylate) standards using the nearest neighbor positions

Polymer Synthesis

Poly(ethylene oxide)-b-poly(ε-caprolactone)-b-poly(L-lactide), PCL-*b*-PEO-*b*-PCL. 0.13 mL of PPA (0.96 mmol), 0.50 mL of *t*-BuP_2 solution (2.0 M in THF, containing 1.0 mmol of *t*-BuP_2) and 20 mL of clean THF were charged into a reaction flask. 5.5 mL of EO (110 mmol) was slowly condensed into the flask at -30 °C. The flask was then sealed by a stopcock and temperature was slowly elevated to 50 °C. After heating and stirring for 72 h, the flask was cooled down to room temperature. Then 2 mL of the reaction mixture was withdrawn in an argon flow and injected into a mixture of 5 mL of THF and a few drops of AcOH. A few drops of this solution was diluted with THF for SEC measurement, the rest was poured into diethyl ether to precipitate PEO. The white powder was then collected, dried in vacuum and used for ^1H NMR and MALDI-TOF measurements. $M_{n,SEC}$ = 4 600 g mol^{-1}, M_w/M_n = 1.03. ^1H NMR (600 MHz, $CDCl_3$): δ/ppm = 7.20-7.15 (aromatic protons on the end group), 3.77-3.49 (–

CH_2CH_2O–), 3.48-3.44 ($PhCH_2CH_2CH_2$–PEO), 2.70-2.66 ($PhCH_2CH_2CH_2$–PEO), 1.93-1.87 ($PhCH_2CH_2CH_2$–PEO); $M_{n,NMR}$ = 4 600 g mol^{-1}.

To the rest of the reaction mixture containing PEO and *t*-BuP_2, 10.0 mL of CL (90.2 mmol) was added in an argon flow. Aliquots were withdrawn (0.1 mL each) in an argon flow in different time intervals. Each aliquot was injected to a mixture of 1.5 mL of $CDCl_3$ and two drops of AcOH. This solution was used for ^1H NMR measurement to determine the conversion of CL. 0.15 mL of such $CDCl_3$ solution was diluted with 1.5 mL of THF for SEC analysis. At 17 h, the conversion of CL reached 61%. 12 mL of the reaction mixture was then withdrawn in an argon flow, injected into a mixture of THF and AcOH, and poured into a cold (-20 °C) mixture of methanol and diethyl ether (1/1, v/v) to precipitate PEO-*b*-PCL diblock copolymer. The white powder was then collected, dried in vacuum and used for SEC and ^1H NMR analysis. $M_{n,SEC}$ = 10 900 g mol^{-1}, M_w/M_n = 1.09. ^1H NMR (600 MHz, $CDCl_3$): δ/ppm = 7.20-7.15 (aromatic protons on the end group), 4.24-4.21 (–PEO–CH_2CH_2OCO–PCL), 4.19-3.91 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 3.77-3.49 (–CH_2CH_2O–), 3.48-3.44 ($PhCH_2CH_2CH_2$–PEO–), 2.70-2.66 ($PhCH_2CH_2CH_2$–PEO–), 2.43-2.17 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.93-1.88 ($PhCH_2CH_2CH_2$–PEO–), 1.77-1.56 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.43-1.33 (–$OCOCH_2CH_2CH_2CH_2CH_2$–); $M_{n,NMR}$(PCL) = 6 800 g mol^{-1}; $M_{n,NMR}$(PEO-*b*-PCL) = 11 400 g mol^{-1}.

To the rest of the reaction mixture containing PEO-*b*-PCL and *t*-BuP_2, 12.0 mL of LLA solution in THF (16.7 mmol of LLA) was quickly added in an argon flow. Aliquots were withdrawn and analyzed in the same manner as described above. The first aliquot was withdrawn at 10 min, which showed that complete conversion of LLA was already reached. After that, SEC traces and ^1H NMR spectra given by all the aliquots remained the same. At 24 h, 0.2 mL of AcOH was added to the reaction mixture, which was then poured into a cold (-20 °C) mixture of methanol and diethyl ether (1/1, v/v) to precipitate PCL-*b*-PEO-*b*-PCL triblock terpolymer. The white powder was then collected, dried in vacuum and used for SEC and ^1H NMR analysis. $M_{n,SEC}$ = 13 300 g mol^{-1}, M_w/M_n = 1.10. ^1H NMR (600 MHz, $CDCl_3$): δ/ppm = 7.20-7.15 (aromatic protons on the end group), 5.30-5.09 (–$OCOCH(CH_3)$–), 4.40-4.33 (–

$OCOCH(CH_3)OH$), 4.24-4.21 (–PEO–CH_2CH_2OCO–PCL–), 4.19-3.91 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 3.77-3.49 (–CH_2CH_2O–), 3.48-3.44 ($PhCH_2CH_2CH_2$–PEO–), 2.70-2.66 ($PhCH_2CH_2CH_2$–PEO–), 2.43-2.17 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.93-1.88 ($PhCH_2CH_2CH_2$–PEO–), 1.77-1.61 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.61-1.44 (–$OCOCH(CH_3)$–), 1.42-1.33 (–$OCOCH_2CH_2CH_2CH_2CH_2$–); $M_{n,NMR}$(PLLA) = 4 700 g mol^{-1}; $M_{n,NMR}$(PCL) = 6 900 g mol^{-1}; $M_{n,NMR}$(PCL-*b*-PEO-*b*-PCL) = 16 200 g mol^{-1}.

Poly(L-lactide)-b-poly(ε-caprolactone)-b-poly(ethylene oxide)-b-poly(ε-caprolactone) -b-poly(L-lactide), PLLA-*b*-PCL-*b*-PEO-*b*-PCL-*b*-PLLA. The preparation of pentablock terpolymer followed a similar procedure. 17 μL of Milli-Q water (0.94 mmol), 0.50 mL of *t*-BuP_2 solution (2.0 M in THF, containing 1.0 mmol of *t*-BuP_2), 20 mL of clean THF and 5.5 mL of EO (110 mmol) were used for the PEO block. After heating at 50 °C and stirring for 72 h, the flask was cooled down to room temperature. 2 mL of the reaction mixture were withdrawn for SEC, ^{1}H NMR and MALDI-TOF analysis. $M_{n,SEC}$ = 3 500 g mol^{-1}, M_w/M_n = 1.12. ^{1}H NMR (600 MHz, $CDCl_3$): δ/ppm = 3.77-3.49 (–CH_2CH_2O–).

10.0 mL of CL (90.2 mmol) was added to the rest of the reaction mixture containing PEO and *t*-BuP_2. Aliquots were withdrawn and analyzed as described above. At 22 h, the conversion of CL reached 72%. 10 mL of the reaction mixture was then withdrawn in an argon flow, injected into a mixture of THF and AcOH, and poured into a cold (-20 °C) mixture of methanol and diethyl ether (1/1, v/v) to precipitate PCL-*b*-PEO-*b*-PCL triblock copolymer. The white powder was then collected, dried in vacuum and used for SEC and ^{1}H NMR analysis. $M_{n,SEC}$ = 12 900 g mol^{-1}, M_w/M_n = 1.08. ^{1}H NMR (600 MHz, $CDCl_3$): δ/ppm = 4.24-4.20 (–PEO–CH_2CH_2OCO–PCL), 4.19-3.91 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 3.77-3.50 (–CH_2CH_2O–), 2.43-2.17 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.77-1.56 (–$OCOCH_2CH_2CH_2CH_2CH_2$–), 1.43-1.33 (–$OCOCH_2CH_2CH_2CH_2CH_2$–); $M_{n,NMR}$(PCL) = 11 200 g mol^{-1} ÷ 2; $M_{n,NMR}$(PCL-*b*-PEO-*b*-PCL) = 14 700 g mol^{-1}.

20.0 mL of LLA solution in THF (27.8 mmol of LLA) was added quickly to the rest of the reaction mixture containing PCL-*b*-PEO-*b*-PCL and *t*-BuP_2. Aliquots were withdrawn and analyzed in the same manner as described above. Complete conversion of LLA was reached at 10 min. After that, SEC traces and ^{1}H NMR spectra given by all the aliquots remained the same. At 24 h, 0.2 mL of AcOH was added to the reaction mixture, which was then poured into a cold (-20 °C) mixture of methanol and diethyl ether (1/1, v/v) to precipitate PLLA-*b*-PCL-*b*-PEO-*b*-PCL-*b*-PLLA pentablock terpolymer. The white powder was then collected, dried in vacuum and used for SEC and ^{1}H NMR analysis. $M_{\mathrm{n,SEC}}$ = 16 100 g mol^{-1}, $M_{\mathrm{w}}/M_{\mathrm{n}}$ = 1.11. ^{1}H NMR (600 MHz, $CDCl_3$): δ/ppm = 5.30-5.09 ($–OCOCH(CH_3)–$), 4.38-4.32 ($–OCOCH(CH_3)OH$), 4.24-4.20 ($–PEO–CH_2CH_2OCO–PCL–$), 4.19-3.91 ($–OCOCH_2CH_2CH_2CH_2CH_2–$), 3.77-3.50 ($–CH_2CH_2O–$), 2.43-2.17 ($–OCOCH_2CH_2CH_2CH_2CH_2–$), 1.77-1.61 ($–OCOCH_2CH_2CH_2CH_2CH_2–$), 1.61-1.44 ($–OCOCH(CH_3)–$), 1.43-1.33 ($–OCOCH_2CH_2CH_2CH_2CH_2–$); $M_{\mathrm{n,NMR}}$(PLLA) = 7 600 g mol^{-1} ÷ 2; $M_{\mathrm{n,NMR}}$(PCL) = 11 400 g mol^{-1} ÷ 2; $M_{\mathrm{n,NMR}}$(PLLA-*b*-PCL-*b*-PEO-*b*-PCL-*b*-PLLA) = 22 500 g mol^{-1}.

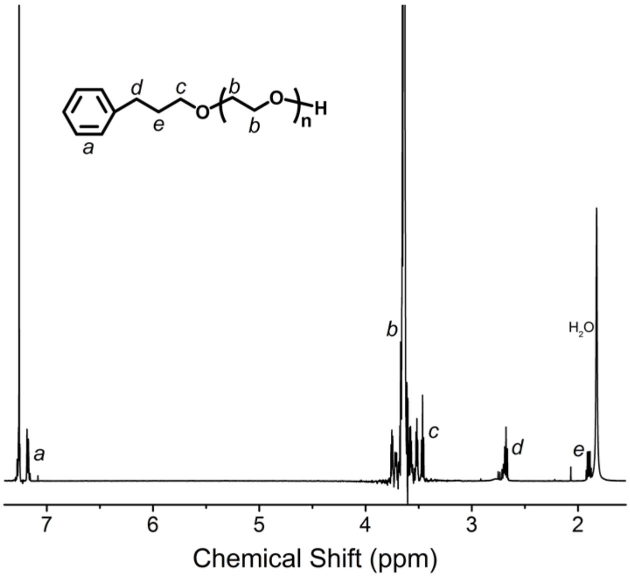

Figure S1 ^{1}H NMR spectra of PEO prepared with 3-phenyl-1-propanol as initiator in the presence of *t*-BuP$_2$.

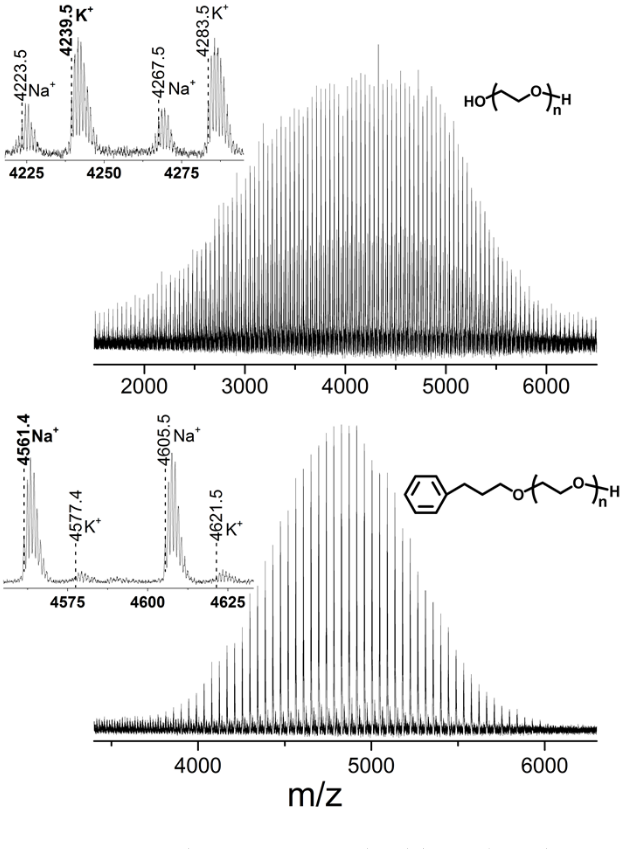

Figure S2 MALDI-TOF spectra of PEO prepared with 3-phenyl-1-propanol (lower figure) and water (upper figure) as initiator in the presence of *t*-BuP$_2$. NaTFA and KTFA are used, respectively, as cationizer. Calculated exact mass for $PhCH_2CH_2CH_2O(C_2H_4O)_{100}H+Na^+$ is 4561.7 Da and for $HO(C_2H_4O)_{95}H+K^+$ is 4239.5 Da, which are in good agreement with the measured values (bold) presented in the insets.

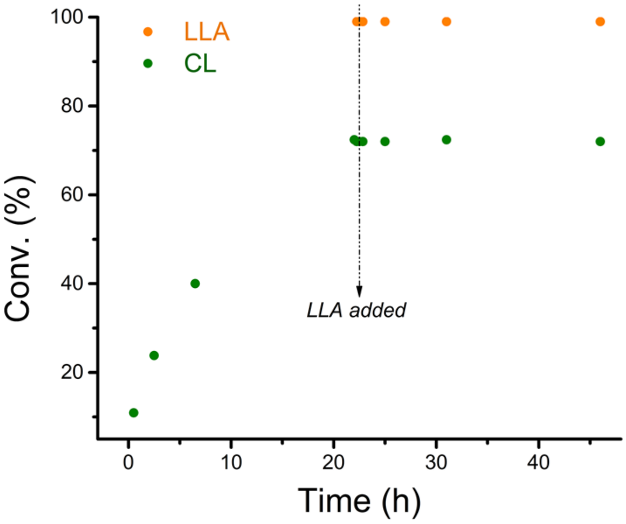

Figure S3 Conversion vs. time plots of ε-caprolactone (green) and L-lactide (orange) in their one-pot sequential polymerization with ethylene oxide using water as initiator in the presence of *t*-BuP$_2$.

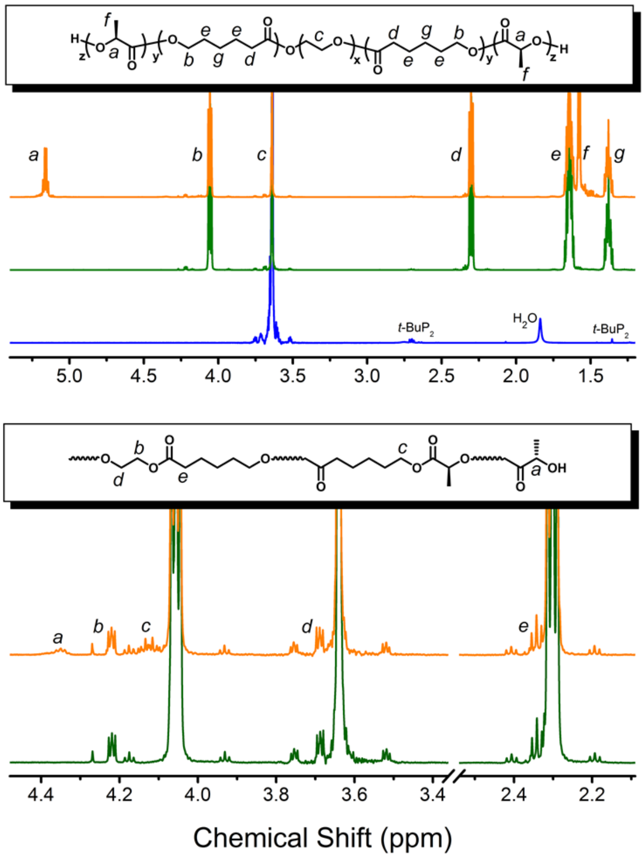

Figure S4 Upper figure: ^{1}H NMR spectra of PEO (blue), PCL-*b*-PEO-*b*-PCL (green) and PLLA-*b*-PCL-*b*-PEO-*b*-PCL-*b*-PLLA (orange) prepared from one-pot sequential polymerization of the three monomers using water as initiator in the presence of *t*-BuP$_2$; lower figure: magnified areas showing signals from the end groups and monomeric units linking different blocks.