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Communication

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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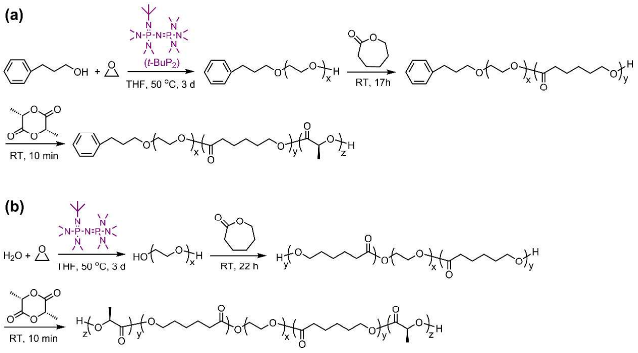
Metal-free polymerization of ethylene oxide (EO) catalyzed by a relatively mild phosphazene base (*t*-BuP$_2$) was proven feasible, which enabled the one-pot sequential polymerization of EO, *ε*-caprolactone, and L-lactide. From either 3-phenyl-1-propanol or water used as initiator, the corresponding triblock or pentablock terpolymer was easily prepared.

Epoxides and cyclic esters share the common feature of generating and maintaining an alkoxide/hydroxyl end group as growing species upon undergoing ring-opening polymerization (ROP). At first glance their sequential polymerization seems facile and the synthesis of the corresponding block copolymers straightforward. However, initiating/catalytic systems that work for epoxides,[1] typically alkali alkoxides, provoke chain transfer reactions (i.e. transesterification on polymer) in the case of cyclic esters, and those that are appropriate for the latter, typically tin or aluminum alkoxides,[2] are irrelevant for the former. On this basis, the synthesis of polyether-polyester block copolymers is possible but tedious as it generally requires multiple steps of synthesis, isolation and purification, etc.[3]

Organic initiators and catalysts have been employed for the polymerizations of a wide range of monomer types.[4] Some of them have shown effectiveness for both epoxides and cyclic esters, for example, *N*-heterocyclic carbenes (NHC).[5] However, to our knowledge, no attempt has been made yet to sequentially polymerize epoxides and cyclic esters using NHCs. Phosphazenes, a family of Brönsted neutral superbases,[6] are another class of organic catalysts that have shown their suitability for the polymerization of a number of cyclic monomers.[7] Due to their high basicity, low nucleophilic character, good solubility in a wide range of solvents, phosphazene bases are used to generate reactive anions and/or improve the nucleophilicity of the initiator/chain end by complexation with the counterion (e.g. proton or lithium cation). Rapid and controlled anionic/pseudo-anionic polymerization ensues, provided the phosphazene base is adequately chosen and finely tuned to the monomer to polymerize. For example, *t*-BuP$_4$, one of the strongest phosphazene base, is well suited for the polymerization of epoxides,[8] but brings about extensive chain transfer reactions in the case of cyclic esters and siloxanes.[9]

The purpose of this study is to investigate the feasibility of using one catalyst to sequentially polymerize ethylene oxide (EO), *ε*-caprolactone (CL) and L-lactide (LLA) in one-pot. As mentioned above, *t*-BuP$_4$ is not an ideal catalyst for cyclic esters. Therefore, a relatively mild phosphazene base, *t*-BuP$_2$, is used in the present study to prepare triblock and pentablock terpolymers consisting of poly(ethylene oxide) (PEO), poly(*ε*-caprolactone) (PCL) and poly(L-lactide) (PLLA).



Scheme 1 Schematic illustration of one-pot sequential polymerization of ethylene oxide, *ε*-caprolactone and L-lactide catalysed by *t*-BuP$_2$ toward (a) triblock terpolymer using 3-phenyl-1-propanol as initiator and (b) pentablock terpolymer using water as initiator.

3-Phenyl-1-propanol (PPA) was used as a representative monohydroxyl initiator (Scheme 1a) with *ca.* 1 equiv. of *t*-BuP$_2$ to catalyze the polymerization of the three monomers (*see Supporting Information for experimental details*). The products were analyzed by size exclusion chromatography (SEC) and nuclear magnetic resonance (NMR). As PEO standards were used for calibration, the molecular weights of PEO samples determined by SEC ($M_{n,SEC}$) can be considered accurate. Matrix assisted laser desorption/ionization time of flight mass spectrometry (MALDI-TOF MS) was also used for the analysis of PEO. After heating at 50 °C for 3 days, the obtained PEO shows a $M_{n,SEC}$ of 4600 g mol^{-1} and a low polydispersity index (M_w/M_n = 1.03). Compared to the molecular weight calculated from the feed ratio ($M_{n,theo}$ = 5000 g mol^{-1}), this indicates an EO conversion of 92%.[10] On the left side of the main RI signal, a small peak is seen which represents *ca.* 1.5% of the total peak area and exhibits a doubled molecular weight (Figure 1, left). However, there is no corresponding UV signal for this peak (Figure 1, right), indicating that the byproduct formed may well be due to the presence of traces of impurity acting as a difunctional initiator. This actually inspired us to use water as initiator for the preparation of pentablock terpolymer, as will be discussed later. The ^{1}H NMR spectrum of the PEO sample isolated shows all the characteristic signals of both PEO and PPA moieties (Figure S1). The molecular weight calculated from the peak integrals ($M_{n,NMR}$ = 4600 g mol^{-1}) fits well with $M_{n,SEC}$. MALDI-TOF MS also confirms the molecular characteristics of the PEO (Figure S2).

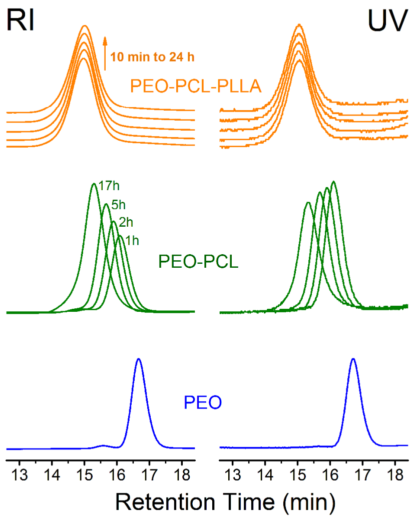


Figure 1 SEC traces of the aliquots withdrawn from the one-pot sequential polymerization of ethylene oxide (blue), ε-caprolactone (green) and L-lactide (orange) using 3-phenyl-1-propanol as initiator in the presence of t-BuP$_2$.

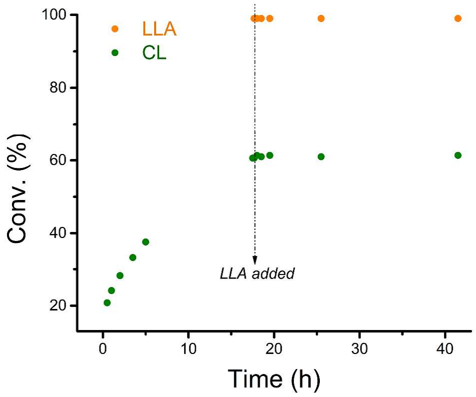


Figure 2 Conversion vs. time plots of ε-caprolactone (green) and L-lactide (orange) in their one-pot sequential polymerization with ethylene oxide using 3-phenyl-1-propanol as initiator in the presence of t-BuP$_2$.

CL was added to the reaction mixture containing PEO and t-BuP$_2$ at room temperature to grow the PCL block. Aliquots were withdrawn for SEC and ^{1}H NMR characterizations. SEC analysis shows a steady increase in molecular weight and a maintained low dispersity (Figure 1), indicating the formation of a well-defined PEO-*b*-PCL diblock copolymer from the PEO precursor. Correspondingly, ^{1}H NMR characterization shows a continuously increasing CL conversion (Figure 2), which reaches 60% after 17 h of reaction. An aliquot was withdrawn and the PEO-*b*-PCL diblock copolymer isolated was characterized by ^{1}H NMR which exhibited all the characteristic signals of PPA, PEO and PCL (Figure 3). The presence of residual EO seemed not to affect the growth of the PCL block.

To the rest of the reaction mixture containing PEO-*b*-PCL and t-BuP$_2$, LLA was introduced as a THF solution. The analysis of the withdrawn aliquots shows that nearly complete conversion of LLA is reached in 10 min (the first aliquot), after which the SEC traces and ^{1}H NMR spectra (monomer conversion) stay unchanged (Figure 1 and 2). The reaction was quenched after 24 h. The isolated final product shows, in its ^{1}H NMR spectrum, all the expected characteristic signals with fitting integrals from the three blocks (Figure 3, upper), from the end groups, and from monomeric units linking different blocks as well (Figure 3, lower).

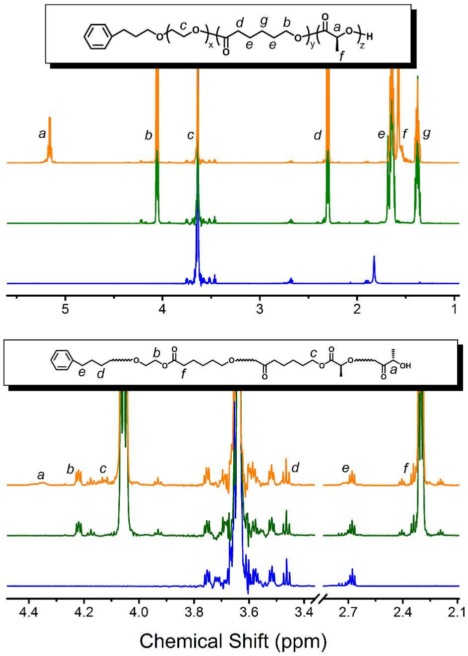


Figure 3 Upper figure: ^{1}H NMR spectra of PEO (blue), PEO-*b*-PCL (green) and PEO-*b*-PCL-*b*-PLLA (orange) prepared from one-pot sequential polymerization of the three monomers using 3-phenyl-1-propanol as initiator in the presence of t-BuP$_2$; lower figure: magnified areas showing signals from the end groups and monomeric units linking different blocks.

LLA is known to polymerize much faster than CL,[11] which enables the achievement of pure PLLA blocks even in the presence of residual CL monomers. Nevertheless, it was surprising to see that after the complete conversion of LLA the residual CL does not polymerize from the hydroxyl end groups carried by the PLLA blocks (Figure 2). The reason is still under investigation, however, this can be considered and utilized as an advantage of this synthetic system, as failure to quench the reaction in time does not result in transesterification (and consequently increased polydispersity) or the undesired further polymerization of residual monomers.

Water was then used as a difunctional initiator to prepare PLLA-*b*-PCL-*b*-PEO-*b*-PCL-*b*-PLLA pentablock terpolymer (Scheme 1b). The PEO obtained in this case shows a tailing in its SEC peak (Figure 4), indicating a slow initiation caused by the poorer nucleophilicity of water compared to a primary alcohol. A lower molecular weight ($M_{n,SEC}$ = 3500 g mol^{-1}) and a higher polydispersity index (M_w/M_n = 1.12) were consequently obtained.[12] $M_{n,SEC}$ and $M_{n,theo}$ indicate a *ca.* 70% EO conversion, however, the following polymerizations of CL and LLA appear to be unaffected by the residual EO.

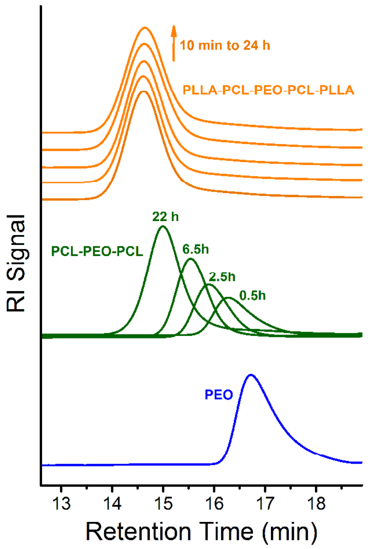


Figure 4 SEC traces given by the aliquots withdrawn from the one-pot sequential polymerization of ethylene oxide (blue), ε-caprolactone (green) and L-lactide (orange) using water as initiator in the presence of *t*-BuP$_2$.

MALDI-TOF spectrum confirms the telechelic dihydroxyl feature of this PEO (Figure S2). As shown by the SEC traces (Figure 4) and monomer conversion plots (Figure S3), the polymerizations of CL and LLA proceed similarly to the case of the triblock terpolymer, i.e., steady and continuous growth of the PCL blocks with 72% of CL conversion reached at 22 h, nearly instant completion of LLA polymerization followed by an unchanged reaction mixture. ^{1}H NMR spectra of the isolated products present all the characteristic signals and fitting integrals (Figure S4), which further confirms the formation of *CBABC* type pentablock terpolymer.

Conclusions

One-pot sequential polymerization of EO, CL and LLA has been proven feasible with a mild phosphazene base (*t*-BuP$_2$) as the common catalyst. Triblock and pentablock terpolymers can be readily obtained using a monohydroxyl compound or water as initiator. The polymerization of EO, which takes a long time in this case, needs to be conducted first becasue if PCL or PLLA was used as initiator for EO, inter/intra-macromolecular transesterification reaction would occur extensively during the polymerization of EO, which would lead to poorly defined products. CL needs to be polymerized before LLA due to the much lower reactivity and the fact that it cannot be initiated by the end group of PLLA in this case. Therefore, it is essential to follow the order of EO-CL-LLA. This study adds to the application of phosphazene bases on polymer synthesis and macromolecular engineering based on organocatalytic polymerizations.

Notes and references

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† Electronic Supplementary Information (ESI) available: [experimental details, additional ^{1}H NMR and MALDI-TOF spectra, kinetic plots]. See DOI: 10.1039/b000000x/

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12 Attempt was made to polymerize propylene oxide with water and *t*-BuP$_2$. No polymer was formed after heating at 50 °C for 3 days.

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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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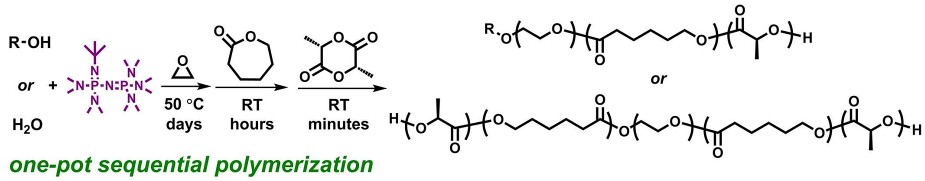

Triblock and pentablock terpolymers are prepared via one-pot sequential polymerization of ethylene oxide, *ε*-caprolactone and L-lactide using a mild phosphazene base as organic catalyst and monoalcohol or water as initiator.