Cyclohexyl-Substituted Polyglycolides with High Glass Transition Temperatures

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ABSTRACT: The substituted glycolides *rac*-dicyclohexylglycolide (*rac*-3,6-dicyclohexyl-1,4-dioxane-2,5-dione), *meso*-dicyclohexylglycolide, *R,R*-dicyclohexylglycolide, and *rac*-methylcyclohexylglycolide (*rac*-3-cyclohexyl-6-methyl-1,4-dioxane-2,5-dione) have been synthesized, and both solution and bulk polymerizations of these monomers are reported. The polymerization kinetics of these new monomers were studied and compared to data for *rac*-diisopropylglycolide (*rac*-3,6-diisopropyl-1,4-dioxane-2,5-dione) and *rac*-lactide. The solution polymerization rates followed the order: *rac*-dicyclohexylglycolide < *rac*-diisopropylglycolide < *rac*-methylcyclohexylglycolide < *rac*-lactide. The glass transition temperature of poly(*rac*-dicyclohexylglycolide) is 98 °C, consistent with a stiff polyglycolide backbone. *meso*-Dicyclohexylglycolide and *R,R*-dicyclohexylglycolide were synthesized and polymerized to study the effect of stereochemistry on the polymer properties. The glass transition temperature of *meso*-dicyclohexylglycolide was 96 °C, while that of poly(*R,R*-dicyclohexylglycolide) increased to 104 °C. While NMR spectroscopy indicated that poly(*R,R*-dicyclohexylglycolide) undergoes minimal racemization during polymerization, differential scanning calorimetry (DSC), X-ray diffraction (XRD), and polarized optical microscopy confirmed that the polymer was amorphous.

Introduction

High molecular weight aliphatic polyesters, a class of biodegradable and biocompatible polymers, have emerged as environmentally friendly, renewable replacements for commodity polymers currently derived from petroleum.[1−5] Of these, polylactide is one of the most widely utilized polyesters because of its biocompatibility and biodegradability, high mechanical strength,[1,2,6,7] and excellent shaping and molding properties.[6,8] Several approaches have been described for altering the physical properties of polymers derived wholly or in part from lactide. These include blending,[9] modifying the ends of polylactide chains,[10] altering the tacticity of lactide polymerization,[11−13] preparing copolymers,[14−27] and polymerizing lactide with macroinitiators to yield comb architectures.[28,29] The use temperature of polylactide for structural applications can be extended beyond the glass transition temperature (T_g) by raising its melting point. This is typically achieved by increasing crystallinity or improving interchain packing through stereocomplexation.[12,30,31] In contrast to the extensive literature for polylactide, there are relatively few reports of analogues where the methyl groups of polylactide are replaced by simple alkyl or aryl groups.[32−35] Most substituted lactides reported to date contain amines, carboxylic acids, or hydroxy groups and were designed with the biological applications of degradable polylactides in mind.[36−43]

One property that should be particularly sensitive to substituent effects is T_g. The T_g's of most lactide homopolymers and copolymers are <60 °C, and efforts to increase T_g by cross-linking have netted only modest improvements.[44] Hence, the relatively low T_g of polylactide limits its use as a rigid, optically clear replacement for large-volume thermoplastics such as polystyrene. It is well known that increasing the rigidity of polymer chains leads to higher T_g's and improved dimensional stability at high temperatures. Taking a cue from polyolefins, the rigidity of the polyester chain can be increased by simply replacing the methyl groups with bulky substituents, such as phenyl or cyclohexyl groups. Previously, we reported that polymerization of 3,6-diphenyl-1,4-dioxane-2,5-dione (mandelide, Scheme 1) yields high molecular weight polymers with T_g > 100 °C.[35] However, the synthesis of mandelide is problematic. Two diastereomers form during the cyclization of mandelic acid, and while *meso*-mandelide (*R,S*-mandelide) can be polymerized under bulk or solution polymerization conditions, *rac*-mandelide (an equal molar mixture of *R,R*-mandelide and *S,S*-mandelide) is insoluble in common solvents and decomposes before melting. Furthermore, *meso*-mandelide is the least stable isomer and readily converts to *rac*-mandelide during purification and polymerization. In addition, polymandelide is prone to thermal and photochemical degradation, which leads to discoloration during melt processing or exposure to light.

The instability of *meso*-mandelide and polymandelide likely stems from reactivity of the benzylic methine hydrogen. Replacing the aromatic ring of polymandelide with a bulky alkyl group is a reasonable strategy for stabilizing the methine hydrogens in the monomer and polymer while maintaining chain rigidity in the substituted polyglycolide. In this Article, we examine the influence of the alkyl group on T_g by systematically varying the glycolide substituent from methyl to isopropyl to cyclohexyl. For simplicity, these monomers (Scheme 1) are systematically named dicyclohexylglycolide (**1**), diisopropylglycolide (**2**), and methylcyclohexylglycolide (**3**).

Experimental Section

Unless otherwise specified, ACS reagent grade starting materials and solvents were used as received from commercial suppliers without further purification. ^{1}H and ^{13}C NMR analyses were carried out at room temperature on a Varian UnityPlus-500 spectrometer at 500 and 125 MHz, respectively, with the chemical shifts reported in ppm and referenced to signals from residual protons in the solvent. IR spectra were acquired using a Mattson Galaxy 3000 FT-IR. Elemental analyses were determined using a Perkin-Elmer 2400 CHNS/O Analyzer. Mass spectral analyses were carried out on a VG Masslab Trio-1. The reported melting points were measured using an Electrothermal capillary melting point apparatus and are uncorrected. Optical rotations were obtained on a Perkin-

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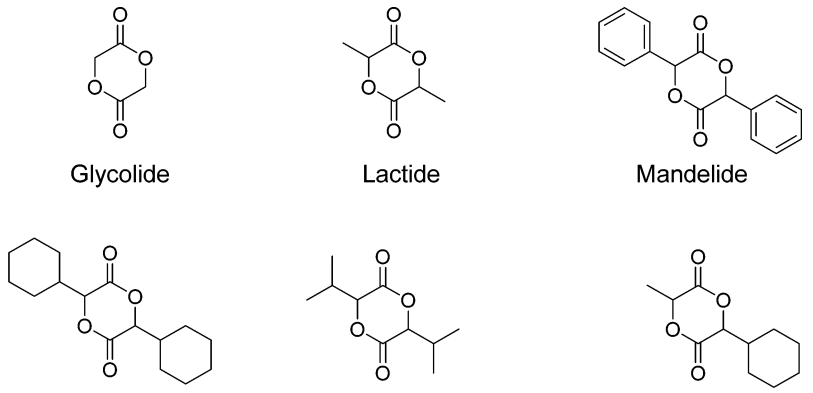
Scheme 1



Elmer 141 polarimeter at 589 nm (sodium D line) using a 1.0 dm cell.

General Procedure for the Reduction of Mandelic Acid. Methanol (200 mL), mandelic acid (Aldrich) (38.0 g, 0.25 mol), acetic acid (2.5 mL), and 7.5 g of 5% rhodium on alumina (Engelhard 5864) were sealed in an autoclave, purged with nitrogen, and then filled with 1400 psig hydrogen gas. Hydrogenation was carried out at room temperature for 8 h, and then the reaction mixture was removed from the autoclave and filtered. After the methanol was evaporated in vacuo, the crude product was recrystallized from toluene.

2-Cyclohexyl-2-hydroxyacetic Acid. Colorless crystals were collected by filtration and dried under vacuum to give 31.8 g (80.5%) of racemic 2-cyclohexyl-2-hydroxyacetic acid. ^{1}H NMR (DMSO-d_6): δ 3.71 (d, J = 4.4 Hz, 1H), 1.66−1.55 (m, 6H), 1.16−1.09 (m, 5H). ^{13}C NMR (DMSO-d_6): δ 175.27, 74.19, 41.15, 28.86, 26.74, 25.84, 25.76, 25.57. IR (KBr): ν (cm^{-1}) 3440, 2933, 2856, 1718, 1450, 1280, 1255, 1230, 1103. Anal. Calcd for $C_8H_{14}O_3$: C, 60.74; H, 8.92. Found: C, 61.12; H, 9.28. mp 135−136 °C [lit.[45] mp 129−130 °C].

(*R*)-(−)-2-Cyclohexyl-2-hydroxyacetic Acid. Colorless crystals were collected by filtration and dried under vacuum to give 19.8 g of (*R*)-(−)-2-cyclohexyl-2-hydroxyacetic acid (92.0% yield from 20.7 g of (*R*)-(−)-mandelic acid). ^{1}H NMR (DMSO-d_6): δ 3.71 (d, J = 4.4 Hz, 1H), 1.69−1.52 (m, 6H), 1.16−1.09 (m, 5H). ^{13}C NMR (DMSO-d_6): δ 175.27, 74.19, 41.15, 28.86, 26.74, 25.84, 25.76, 25.57. IR (KBr): ν (cm^{-1}) 3442, 2935, 2854, 1716, 1452, 1280, 1261, 1232, 1112, 1099. Anal. Calcd for $C_8H_{14}O_3$: C, 60.74; H, 8.92. Found: C, 60.89; H, 8.90. mp 124−126 °C [lit.[46] mp 130−131 °C]. $[\alpha]^{20}_D = -12.0°$ (c = 1.0, CH_3OH) [lit.[46] $[\alpha]^{25}_D = -15.5°$ (c = 0.4, CH_3OH)]. The ^{1}H NMR spectrum of the ester formed from (*R*)-(−)-2-cyclohexyl-2-hydroxyacetic acid and (1*R*,2*S*,5*R*)-menthol indicated an optical purity >99% ee.

General Procedure for the Syntheses of Symmetrical Substituted Glycolides. A mixture of 0.16 mol of the appropriate α-hydroxy acid and 1.0 g of *p*-toluenesulfonic acid in 1600 mL of toluene was refluxed for 6 days with the water removed azeotropically via a Dean−Stark trap. After the mixture was cooled to room temperature, toluene was removed by rotary evaporation, and the resulting solid was dissolved in ethyl acetate. The solution was washed with saturated $NaHCO_3$ and dried over $MgSO_4$. After ethyl acetate was removed, the crude product was recrystallized from cyclohexane, hexane, or toluene.

3,6-Dicyclohexyl-1,4-dioxane-2,5-dione (1). *rac*-Dicyclohexylglycolide was recrystallized from toluene, and then from cyclohexane. The colorless crystals were collected by filtration and dried under vacuum to give 4.8 g (21%) of *rac*-dicyclohexylglycolide. ^{1}H NMR ($CDCl_3$): δ 4.66 (d, J = 3.4 Hz, 2H), 2.20−2.12 (m, 2H), 1.86−1.64 (m, 10H), 1.54−1.43 (dq, J = 3.7 Hz, J = 12.8 Hz, 2H), 1.37−1.24 (m, 6H), 1.22−1.11 (m, 2H). ^{13}C NMR ($CDCl_3$): δ 166.24, 79.33, 38.82, 28.94, 26.11, 25.75, 25.73 (peaks at 25.75 and 25.73 ppm were resolved into three separate peaks by adding the NMR shift reagent europium(III) tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorate)). IR (KBr): ν (cm^{-1}) 2930, 2852, 1758, 1451, 1370, 1303, 1261, 1185, 1111. Anal. Calcd for $C_{16}H_{24}O_4$: C, 68.54; H, 8.63. Found: C, 68.73; H, 8.51. MS (EI) *m*/*z* 198.1 (100), 123.0 (24), 94.9 (72), 54.9 (41). mp 183−185 °C. The toluene mother liquor from the initial recrystallization of *rac*-dicyclohexylglycolide was evaporated to dryness, and the residue was crystallized from hexane to provide crude *meso*-dicyclohexylglycolide. Separation from residual *rac*-dicyclohexylglycolide was achieved by column chromatography on silica gel (ether/hexanes 1/3) to give 0.86 g (3.8%) of *meso*-dicyclohexylglycolide. ^{1}H NMR ($CDCl_3$): δ 4.72 (d, J = 4.9 Hz, 2H), 2.12−2.03 (m, 2H), 1.86−1.64 (m, 10H), 1.46−1.35 (dq, J = 3.5 Hz, J = 12.5 Hz, 2H), 1.34−1.11 (m, 8H). ^{13}C NMR ($CDCl_3$): δ 165.22, 80.59, 80.56, 41.02, 28.57, 26.82, 25.77, 25.54, 25.52. IR (KBr): ν (cm^{-1}) 2929, 2852, 1752, 1450, 1379, 1308, 1274, 1110. Anal. Calcd for $C_{16}H_{24}O_4$: C, 68.54; H, 8.63. Found: C, 68.93; H, 8.51. MS (EI) *m*/*z* 198.1 (100), 123.0 (27), 94.9 (77), 54.9 (54). mp 80.5−81.5 °C.

(3*R*,6*R*)-(+)-3,6-Dicyclohexyl-1,4-dioxane-2,5-dione (1). *R*,*R*-Dicyclohexylglycolide was recrystallized from cyclohexane. The colorless crystals were collected by filtration and dried under vacuum to give 4.5 g of *R*,*R*-dicyclohexylglycolide (40% yield from 12.7 g of (*R*)-(−)-2-cyclohexyl-2-hydroxyacetic acid). ^{1}H NMR ($CDCl_3$): δ 4.66 (d, J = 2.9 Hz, 2H), 2.20−2.11 (m, 2H), 1.85−1.65 (m, 10H), 1.53−1.43 (dq, J = 3.5 Hz, J = 12.8 Hz, 2H), 1.37−1.24 (m, 6H), 1.22−1.11 (m, 2H). ^{13}C NMR ($CDCl_3$): δ 166.27, 79.27, 38.76, 28.90, 26.07, 25.71, 25.70. IR (KBr): ν (cm^{-1}) 2932, 2853, 1760, 1452, 1371, 1302, 1256, 1253, 1185, 1113. Anal. Calcd for $C_{16}H_{24}O_4$: C, 68.54; H, 8.63. Found: C, 68.78; H, 8.67. MS (EI) *m*/*z* 198.1 (100), 123.0 (25), 94.9 (75), 54.9 (44). mp 194−196 °C. $[\alpha]^{20}_D = +190.0°$ (c = 1.0, $CHCl_3$).

***rac*-3,6-Diisopropyl-1,4-dioxane-2,5-dione (2).** *rac*-Diisopropylglycolide was recrystallized from toluene, and contamination from residual *meso*-diisopropylglycolide was eliminated by column chromatography on silica gel (ether/hexane 1/2) to give 1.5 g of *rac*-diisopropylglycolide (16% yield from 10.7 g of *rac*-2-hydroxy-3-methylbutyric acid). ^{1}H NMR ($CDCl_3$): δ 4.70 (d, J = 3.1 Hz, 2H), 2.57−2.46 (m, 2H), 1.19−1.14 (d, J = 6.9 Hz, 6H), 1.09−1.04 (d, J = 6.9 Hz, 6H). ^{13}C NMR ($CDCl_3$): δ 166.33, 79.59, 29.42, 18.59, 15.85. IR (KBr): ν (cm^{-1}) 2975, 2940, 2881, 1753, 1473, 1367, 1311, 1257, 1134, 1043. Anal. Calcd for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05. Found: C, 60.45; H, 7.83. MS (EI) *m*/*z* 158.0 (73), 84.0 (38), 82.8 (39), 68.9 (100), 56.0 (59), 40.9 (40). mp 137.0−137.5 °C.

3-Cyclohexyl-6-methyl-1,4-dioxane-2,5-dione (3). To a 500 mL three-neck flask were added 12.7 g (0.08 mol) of 2-cyclohexyl-2-hydroxyacetic acid, 20.7 g (0.096 mol) of 2-bromopropionyl bromide, and 200 mL of THF. The flask was purged with nitrogen and then cooled in a salt-ice bath. A mixture of 14.5 mL of Et_3N and 50 mL of THF was added dropwise under mechanical stirring, and the solution was cooled and stirred overnight. The solution was filtered to remove a white solid, and the filtrate was evaporated

to dryness. The resulting solid was dissolved in ethyl acetate, washed with 2 M HCl (3 × 100 mL), saturated aqueous NaCl, dried over $MgSO_4$, and then concentrated to give a solution of the crude linear acid ester. The viscous liquid was mixed with 1600 mL of acetone and 27 g of $NaHCO_3$, and refluxed for 2 days. The solids were removed by filtration, and the acetone was evaporated to dryness. The crude product was dissolved in ethyl acetate, dried over $MgSO_4$, and the ethyl acetate was removed by rotary evaporation. The crude product was recrystallized from cyclohexane, and the colorless crystals were collected by filtration and dried under vacuum to give 10.0 g (59%) of *rac*-methylcyclohexylglycolide. ^{1}H NMR ($CDCl_3$): δ 4.97 (q, J = 6.8 Hz, 1H), 4.71 (d, J = 2.9 Hz, 1H), 2.20−2.12 (m, 1H), 1.86−1.64 (m, 8H), 1.54−1.44 (dq, J = 3.8 Hz, J = 12.7 Hz, 1H), 1.38−1.25 (m, 3H), 1.23−1.12 (m, 1H). ^{13}C NMR ($CDCl_3$): δ 167.50, 166.02, 79.64, 72.12, 38.68, 28.93, 26.09, 25.74, 15.99. IR (KBr): ν (cm^{-1}) 2999, 2939, 2853, 1763, 1761, 1451, 1379, 1341, 1296, 1245, 1184, 1098. Anal. Calcd for $C_{11}H_{16}O_4$: C, 62.25; H, 7.60. Found: C, 62.34; H, 7.67. MS (EI) *m*/*z* 129.9 (100), 83.0 (10), 56.0 (13), 55.0 (26). mp 80.5−82.0 °C. The cis relationship of the methyl and cyclohexyl groups on the glycolide ring was verified by 1D gradient-selected transient nuclear Overhauser effect spectroscopy (NOESY1D).

Solution Polymerization of Substituted Glycolides. A Schlenk flask containing 2.0 mmol of substituted glycolide and a magnetic stir bar was fitted with a septum and then evacuated and refilled with argon three times. Predetermined amounts of anhydrous toluene, and toluene solutions of Sn(2-ethylhexanoate)$_2$ and 4-*tert*-butylbenzyl alcohol were then added via syringe through the septum to yield a 0.2 M monomer concentration. The Schlenk flask was then suspended in a 90 °C oil bath to initiate polymerization. For kinetic studies, a syringe was used to remove aliquots from the reaction at specific intervals, and the samples were analyzed by ^{1}H NMR to determine the monomer conversion.

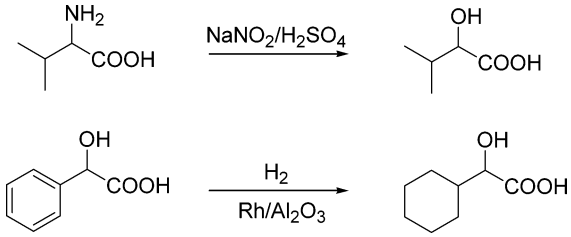
Bulk Polymerization of Substituted Glycolides. Solvent-free polymerizations were carried out in sealed ampules prepared from 3/8 in. diameter glass tubing. Ampules were charged with monomer and a stir bar and connected via a Cajon fitting to a T-shaped vacuum adapter fitted with a stopcock and an air-free Teflon valve. A septum was attached to the outlet of the stopcock, and the apparatus was connected to a vacuum line and evacuated through the Teflon valve. After 2 h, the ampule was backfilled with argon, and a syringe was used to add predetermined amounts of the Sn(2-ethylhexanoate)$_2$ and 4-*tert*-butylbenzyl alcohol solutions to the ampules through the stopcock. The solvent was removed in vacuo, and the ampule was flame-sealed and immersed in an oil bath. At the end of the polymerization, the ampule was cooled, opened, and the polymer was dissolved in CH_2Cl_2. A portion of the solution was evacuated to dryness and analyzed by NMR for conversion. The remaining polymer solution was precipitated three times into cold methanol, dissolved in 100 mL of CH_2Cl_2, and washed with 2 M HCl. After the CH_2Cl_2 solution was concentrated to ∼10 wt %, reprecipitation into cold methanol gave polymer free of residual monomer and catalysts.

Polymer Characterization. Polymer molecular weights were determined by gel permeation chromatography (GPC) using a PLgel 20 m Mixed A column and a Waters 2410 differential refractometer detector at 35 °C. THF was used as the eluting solvent at a flow rate of 1 mL/min, and monodisperse polystyrene standards were used to calibrate the molecular weights. Differential scanning calorimetry (DSC) analyses of the polymers were obtained using a TA DSC Q100. Samples were run under a nitrogen atmosphere at a heating rate of 10 °C/min, with the temperature calibrated with an indium standard. Thermogravimetric analyses (TGA) were run both in air and under nitrogen at a heating rate of 10 °C/min using a Perkin-Elmer TGA 7.

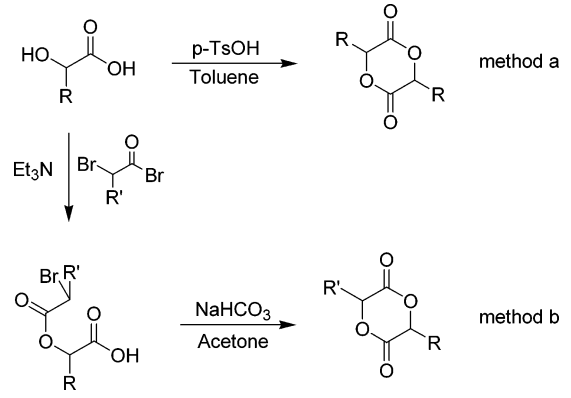
Results and Discussion

Monomer Synthesis. The α-hydroxy acids used to prepare substituted glycolide monomers were commercial products or, as in the case of 2-cyclohexyl-2-hydroxyacetic acid and 2-hydroxy-3-methylbutanoic acid, synthesized from naturally occurring α-hydroxy acids or amino acids. Specifically, 2-cyclohexyl-2-hydroxyacetic acid was prepared from mandelic acid by catalytic hydrogenation using rhodium on alumina,[47,48] while 2-hydroxy-3-methylbutanoic acid was prepared by diazotization of DL-valine[49] and subsequent displacement of the diazonium group by a hydroxyl group (Scheme 2). The conversion of α-hydroxy acids to symmetrical and unsymmetrical glycolides followed two previously reported synthetic protocols (Scheme 3).[32,50] Symmetrical monomers were prepared via acid-catalyzed condensation of the α-hydroxy acids in toluene, removing the water by azeotropic distillation. Run in dilute solution to minimize formation of linear oligomers, mixtures of *R*,*S* (meso) and *R*,*R*/*S*,*S* (rac) diastereomers were obtained in 20−40% yield. The remaining material was a mixture of low molecular weight oligomers and unreacted α-hydroxy acid, which could be recycled to improve the glycolide yield. To prepare the unsymmetrical methylcyclohexylglycolide, 2-cyclohexyl-2-hydroxyacetic acid was condensed with 2-bromopropionyl bromide. Next, ring-closure was effected by treating the resulting ω-bromo carboxylic acid with mild base. This route favors the formation of racemic products, with the meso diastereomer as a minor component.

Scheme 2



Scheme 3



To compare the effects of different substituents on polymer properties and polymerization kinetics, we polymerized glycolides substituted with methyl, isopropyl, and cyclohexyl groups. For consistency, all polymers were prepared from racemic glycolides that had been purified by recrystallization and/or column chromatography to remove meso contaminants. Representative NMR spectra of *rac*-dicyclohexylglycolide and its polymer are shown in Figure 1. The 500 MHz ^{1}H NMR spectrum of the monomer shows the expected doublet for the methine protons at 4.66 ppm and no evidence of contamination from the meso diastereomer.[32]

After polymerization, the signals from the methine protons broaden and shift downfield to 4.94 and 5.06 ppm, allowing simple calculation of conversion from the integrated intensities of the monomer and polymer methine signals.

Solution Polymerization Kinetics. Solution polymerizations of racemic glycolides using Sn(2-ethylhexanoate)$_2$ as the catalyst

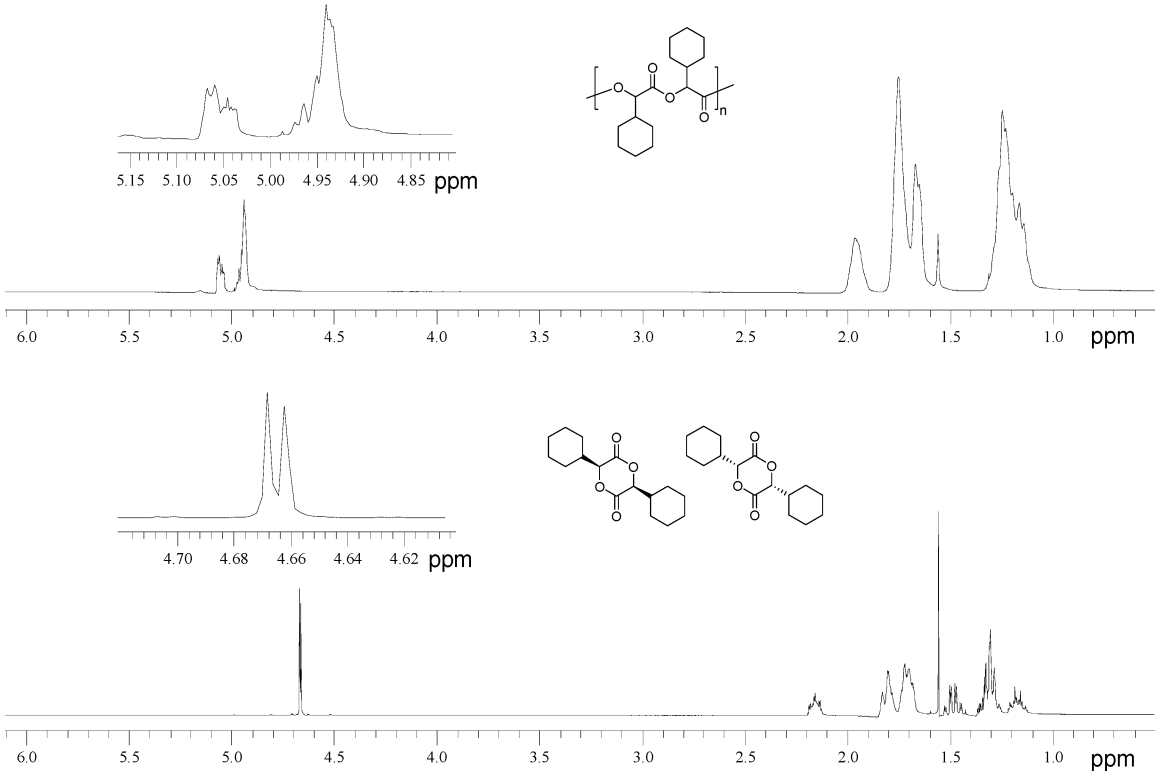


Figure 1. 500 MHz ^{1}H NMR spectra of *rac*-dicyclohexylglycolide and poly(*rac*-dicyclohexylglycolide).

and 4-*tert*-butylbenzyl alcohol as the initiator were carried out in toluene to evaluate the effect of the size of glycolide ring substituents on the rate of polymerization. Ring-opening polymerizations of lactide derivatives initiated by alcohols and catalyzed by Sn(2-ethylhexanoate)$_2$ typically follow first-order kinetics at low conversions.[32,51,52] Polymerizations at 90 °C with relatively low monomer concentrations (∼0.2 M) and initiator and catalyst loadings (1 mol %) are easily controlled, depolymerization and equilibrium affects are negligible, and the polymerization can be treated as an irreversible reaction[51] as expressed in eq 1:

$$R = -\frac{\mathrm{d[M]}}{\mathrm{d}t} = k_\mathrm{p}[\mathrm{M}][\mathrm{I}] \qquad (1)$$

where k_p is the apparent rate constant for propagation and [M] and [I] are the concentrations of monomer and initiator, respectively. For a living polymerization, [I] is a constant. Therefore, a plot of $-\ln([\mathrm{M}]_t/[\mathrm{M}]_0)$, where $[\mathrm{M}]_t$ is the concentration of the monomer at time t and $[\mathrm{M}]_0$ is the initial monomer concentration, versus time t should be linear with slope $k_\mathrm{p}[\mathrm{I}]$.

The data shown in Figure 2 are consistent with simple first-order kinetics. As expected, k_p (Table 1) depended on the size of the glycolide ring substituents, with the polymerization of *rac*-dicyclohexylglycolide being the slowest, 70× slower than k_p of *rac*-lactide. While the isopropyl group should be a reasonable steric mimic for the cyclohexyl group, the polymerization rate of *rac*-diisopropylglycolide is 4× faster than that of *rac*-dicyclohexylglycolide. The results for *rac*-methylcyclohexylglycolide are particularly interesting. The polymerization rate is ∼10× that of *rac*-dicyclohexylglycolide, implying preferential ring opening at the carbonyl adjacent to methyl group and an alternating sequence of methyl and cyclohexyl groups along the polymer backbone (Figure S1). Similar results have been reported for the polymerization of 3-methyl-1,4-dioxan-2,5-dione, where ^{13}C NMR data confirm a highly alternating pattern of glycolic and lactic acid residues in the polymer backbone.[53] With the increasing interest in functional polylactides for medical applications,[36,37,40,41,54,55] further studies of the polymerization of nonsymmetrical monomers are warranted.

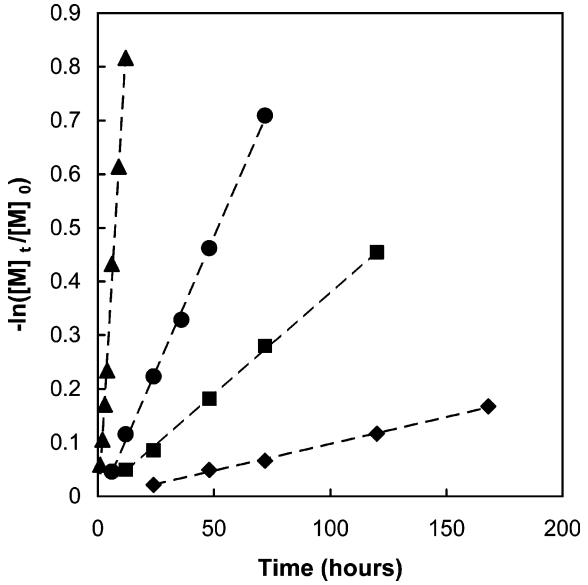


Figure 2. Kinetics of solution polymerization of *rac*-lactide (▲), *rac*-methylcyclohexylglycolide (●), *rac*-diisopropylglycolide (■), and *rac*-dicyclohexylglycolide (◆). Polymerization conditions: 90 °C, [Sn(2-ehylhexanoate)$_2$]/[4-*tert*-butylbenzyl alcohol] = 1, [monomer]/[catalyst] = 100.

Table 1. Solution Polymerization Rates of Substituted Glycolides

monomer	k_p (L s^{-1} mol^{-1}) × 10^6	relative rate
rac-lactide	98.7	71
rac-methylcyclohexylglycolide	13.8	9.9
rac-diisopropylglycolide	5.28	3.8
rac-dicyclohexylglycolide	1.39	1

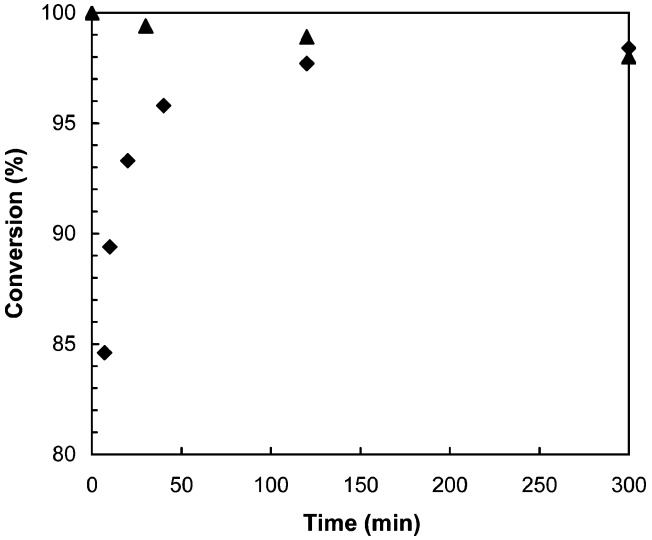


Figure 3. Polymerization and depolymerization data for *rac*-dicyclohexylglycolide: polymerization (◆), depolymerization (▲). Conditions: 200 °C, [Sn(2-ethylhexanoate)$_2$]/[4-*tert*-butylbenzyl alcohol] = 1, [monomer]/[catalyst] = 100.

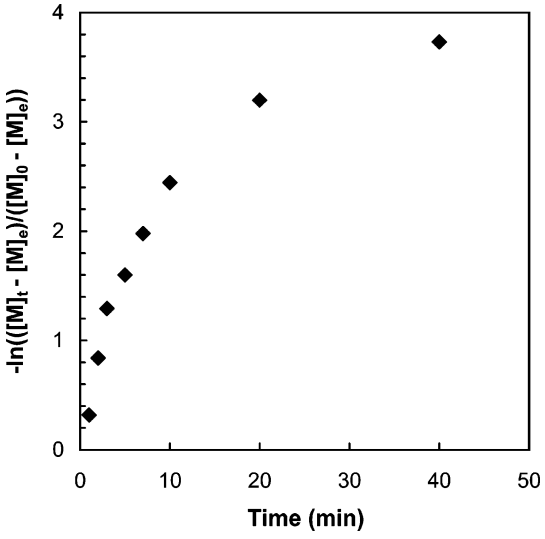


Figure 4. Kinetic data for the bulk polymerization of *rac*-dicyclohexylglycolide assuming an equilibrium monomer concentration of 2% (~0.07 M). Polymerization conditions: 200 °C, [Sn(2-ethylhexanoate)$_2$]/[4-*tert*-butylbenzyl alcohol] = 1, [monomer]/[catalyst] = 100.

Bulk Polymerization Kinetics. We examined the kinetic behavior of bulk polymerizations of *rac*-dicyclohexylglycolide because solvent-free polymerizations were used to generate most materials used for characterization. The kinetic data were taken at 200 °C because the monomer melts at >180 °C. Bulk polymerizations of *rac*-dicyclohexylglycolide were carried out by loading monomer with 1 mol % Sn(2-ethylhexanoate)$_2$ and 4-*tert*-butylbenzyl alcohol into glass tubes and sealing the tubes under vacuum. The tubes were immersed in a 200 °C bath and removed at desired times. High-temperature runs introduce two complications: high polymerization rates make collecting data at low conversions problematic, and because the polymerizations run to high conversions, the polymerization/depolymerization equilibrium must be included in the kinetic analysis.[32,51] The first-order kinetic equation is revised to account for equilibrium monomer concentration [M]$_{eq}$ as shown in eq 2.

$$-\ln\left(\frac{[\mathrm{M}]_t - [\mathrm{M}]_{eq}}{[\mathrm{M}]_0 - [\mathrm{M}]_{eq}}\right) = k_p[\mathrm{I}]t \qquad (2)$$

The equilibrium monomer concentration was determined from the limiting conversion reached during 200 °C polymerizations, as well as depolymerization experiments carried out at the same temperature by adding Sn(2-ethylhexanoate)$_2$ to poly(*rac*-dicyclohexylglycolide) that had been purified by dissolving in CH_2Cl_2, washing with HCl, and precipitation into methanol to remove all traces of monomer. Both experiments (Figure 3) gave ~2% residual monomer, from which we estimate [M]$_{eq}$ = 0.07 M.

The data for the bulk polymerization at of *rac*-dicyclohexylglycolide are plotted in Figure 4, assuming 2% residual monomer. The points correspond to the average from three independent runs, except for the data at 3, 7, and 40 min, where only two samples were taken. The data are decidedly curved. We suspect that polymerization conditions are sufficiently severe to cause a loss in active chain ends during polymerization. NMR spectra of polymers taken after extended melt polymerization show traces of an aldehyde byproduct, analogous to the formation of benzaldehyde during the thermal degradation of polymandelide at 200 °C.[35] A linear fit for the kinetic data can be obtained by assuming that the population of growing chain end decays according to eq 3, where k_d is the rate constant for the decomposition process. However, the exact mechanism for the loss of chain is unknown.

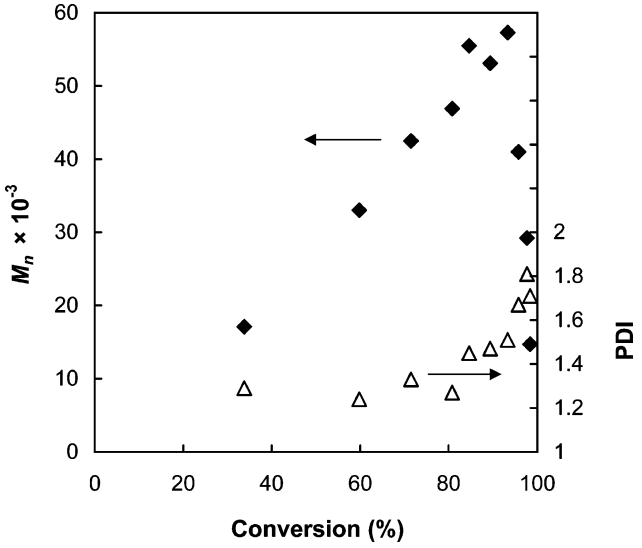


Figure 5. Number-average molecular weight (◆) and polydispersity (□) versus conversion for the bulk polymerization of *rac*-dicyclohexylglycolide. Polymerization conditions: 200 °C, [Sn(2-ethylhexanoate)$_2$]/[4-*tert*-butylbenzyl alcohol] = 1, [monomer]/[catalyst] = 100.

$$[\mathrm{I}] = [\mathrm{I}]_0 e^{-k_d t} \qquad (3)$$

Figure 5 shows the evolution of the number-average molecular weight (M_n) and polydispersity (PDI) with conversion during the bulk polymerization of *rac*-dicyclohexylglycolide. As monomer conversion increases during bulk polymerization, M_n increases, reaches a maximum at high conversion, and then decreases. The PDI is nearly constant until 80% conversion and then increases sharply. This behavior is consistent with the known mechanism for ring-opening polymerization of lactides.[32] At low conversion, M_n increases linearly with conversion with an almost constant PDI because of the "living" nature of the polymerization. When the monomer is nearly consumed, transesterification becomes competitive with propagation, increasing the PDI, and formation of cyclic esters via intramolecular transesterification causes a reduction in M_n. Obviously, the

Table 2. Properties of Polyglycolides

polymer	$M_n \times 10^{-3}$	M_w/M_n	T_g (°C)
poly(*rac*-lactide)[a]	82.9	1.39	55
poly(*rac*-diisopropylglycolide)[b]	89.3	1.18	41
poly(*rac*-methylcyclohexylglycolide)[a]	40.5	1.27	73
poly(*rac*-dicyclohexylglycolide)[c]	99.3	1.38	98
poly(*meso*-dicyclohexylglycolide)[a]	89.7	1.22	96
poly(*R,R*-dicyclohexylglycolide)[c]	102.5	1.42	104

[a] Bulk polymerized at 130 °C. [b] Bulk polymerized at 150 °C. [c] Bulk polymerized at 200 °C.

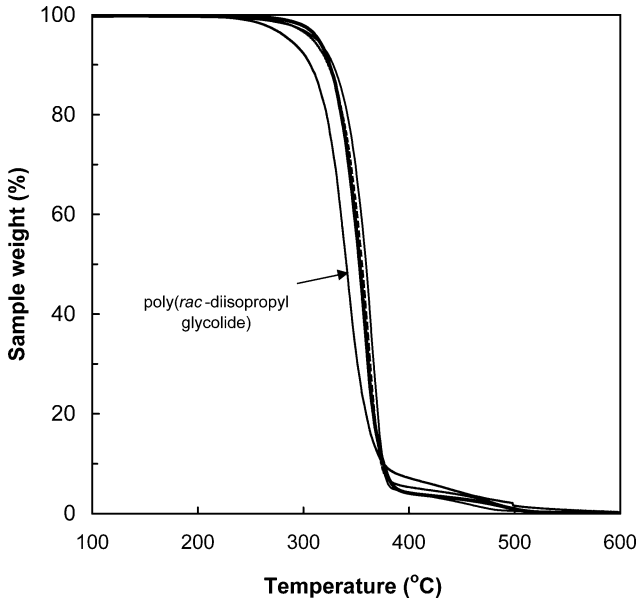


Figure 6. Thermogravimetric analysis results for substituted polyglycolides run in air at a heating rate of 10 °C/min. Data are shown for poly(*rac*-lactide), poly(*rac*-methylcyclohexylglycolide), poly(*rac*-dicyclohexylglycolide), and poly(*rac*-diisopropylglycolide). The trace for poly(*rac*-diisopropylglycolide) is marked in the figure; data for the other polymers are nearly co-incident.

kinetic data described earlier point to thermal degradation as an additional mechanism that can lower M_n and increase PDI.[56]

Polymer Properties. Polymer properties were measured using materials prepared by bulk polymerizations with a monomer to initiator ratio of 300. The crude polymers were purified by precipitation into cold methanol to remove monomers, washed with dilute HCl to remove catalyst residues, and then dried to constant weight. Representative data for the polymers are shown in Table 2. The polymer molecular weights ranged from $M_n = 40\,000$ to 100 000 g/mol with polydispersities <1.5. The decomposition temperatures of polymers measured using thermogravimetric analysis (TGA) define the limiting use temperature of the polymers. As shown in Figure 6, the TGA traces for the polymers are similar with onsets for weight loss near 300 °C followed by nearly complete weight loss. TGA runs in air and nitrogen show only slight differences in their decomposition curves.

Glass transition temperatures measured by DSC are shown in Table 2. The DSC traces are shown in Figure S2, Supporting Information. In agreement with the notion that cyclohexyl substituents would increase the rotation barriers of polyglycolide polymers and increase T_g, poly(*rac*-dicyclohexylglycolide) has the highest T_g (98 °C), 43 °C higher than that of poly(*rac*-lactide). The effects of the cyclohexyl ring on T_g were significant even for the non-symmetrical poly(*rac*-methylcyclohexylglycolide) ($T_g = 73$ °C).

Somewhat surprising was a T_g of 41 °C for poly(*rac*-diisopropylglycolide), 14 °C lower than that of poly(*rac*-lactide)

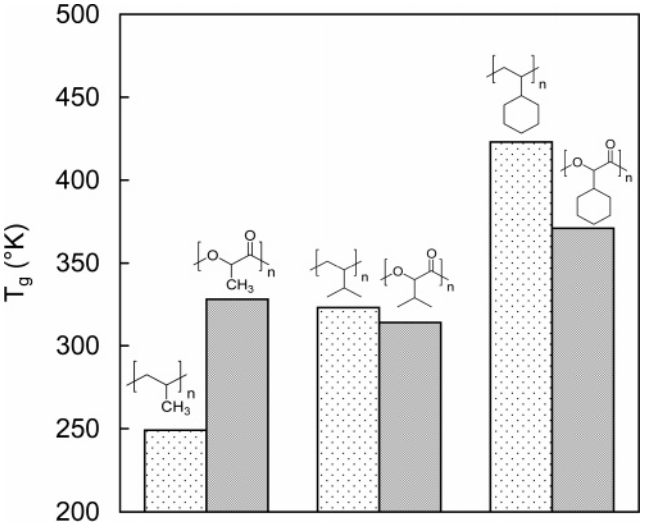


Figure 7. Comparison of T_g's between polyglycolides and structurally related polyolefins.

of comparable molecular weight. The kinetic data shown in Figure 2 for the polymerization of these monomers suggest that the steric demands of the isopropyl group are comparable to those of the cyclohexyl group and would predict a T_g higher than was measured. These data point to the importance of polar groups in determining polymer T_g's, such as the intermolecular dipole−dipole interactions and weak C−H···O hydrogen bonds in polylactides.[57] When van der Waals interactions dominate chain−chain interactions, T_g tracks the increase in rotation barriers. For example, polypropylene, poly(3-methyl-1-butene), and poly(vinyl cyclohexane) have T_g's of −40, 50, and 148 °C, respectively.[58,59] When dipole−dipole interactions become important, as in the case of polylactides, bulky side chains not only increase rotation barriers (increase T_g), but also interrupt dipole−dipole interactions (decrease T_g), by shielding ester groups from each other (Figure 7). Apparently for poly(*rac*-diisopropylglycolide), the increase in the rotational barrier caused by the isopropyl groups cannot fully compensate for the decrease of dipole−dipole interactions, which leads to a lower T_g than poly(*rac*-lactide).

We made a preliminary assessment of the rheological properties of poly(dicyclohexylglycolide). The terminal viscosity and storage modulus data from a high molecular weight sample ($M_n = 58\,000$, PDI = 1.46) are consistent with polystyrene-like properties (Figure S-4, Supporting Information). Furthermore, the plateau modulus, an indicator of the molecular weight between entanglements, is comparable to that of polystyrene, suggesting the flow properties of poly(dicyclohexylglycolide) also are similar.

Degradation experiments in phosphate buffer at 55 °C showed no appreciable loss in molecular weight or mass after 100 days, probably due to the polymer's high T_g. An 8% weight loss in 90 days for polymandelide under the same condition suggests that the hydrophobic cyclohexyl rings of poly(dicyclohexylglycolide) also may contribute to a low degradation rate. As an alternative to hydrolytic degradation, we explored transesterification for the recycling/recovery of poly(dicyclohexylglycolide). Heating the polymer in refluxing *n*-butanol (bp = 117 °C) with Sn(2-ethylhexanoate)$_2$ provided the corresponding ester in several days, but ethanol was ineffective because its boiling point is below the poly(dicyclohexylglycolide) T_g.

Stereochemical Effects. Polymer stereoregularity that leads to crystallinity is a major factor in determining the physical properties and applications for polylactides.[60−65] To understand

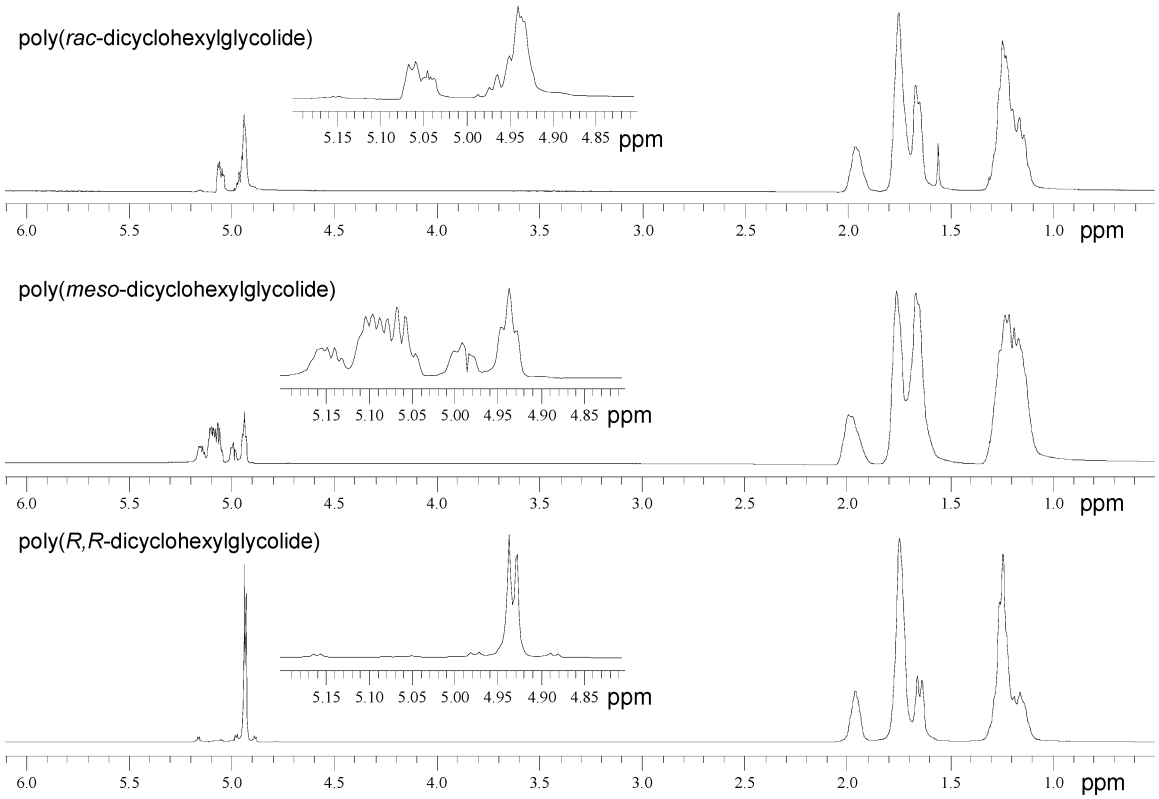


Figure 8. 500 MHz ^{1}H NMR spectra for poly(*rac*-dicyclohexylglycolide), poly(*meso*-dicyclohexylglycolide), and poly(*R,R*-dicyclohexylglycolide).

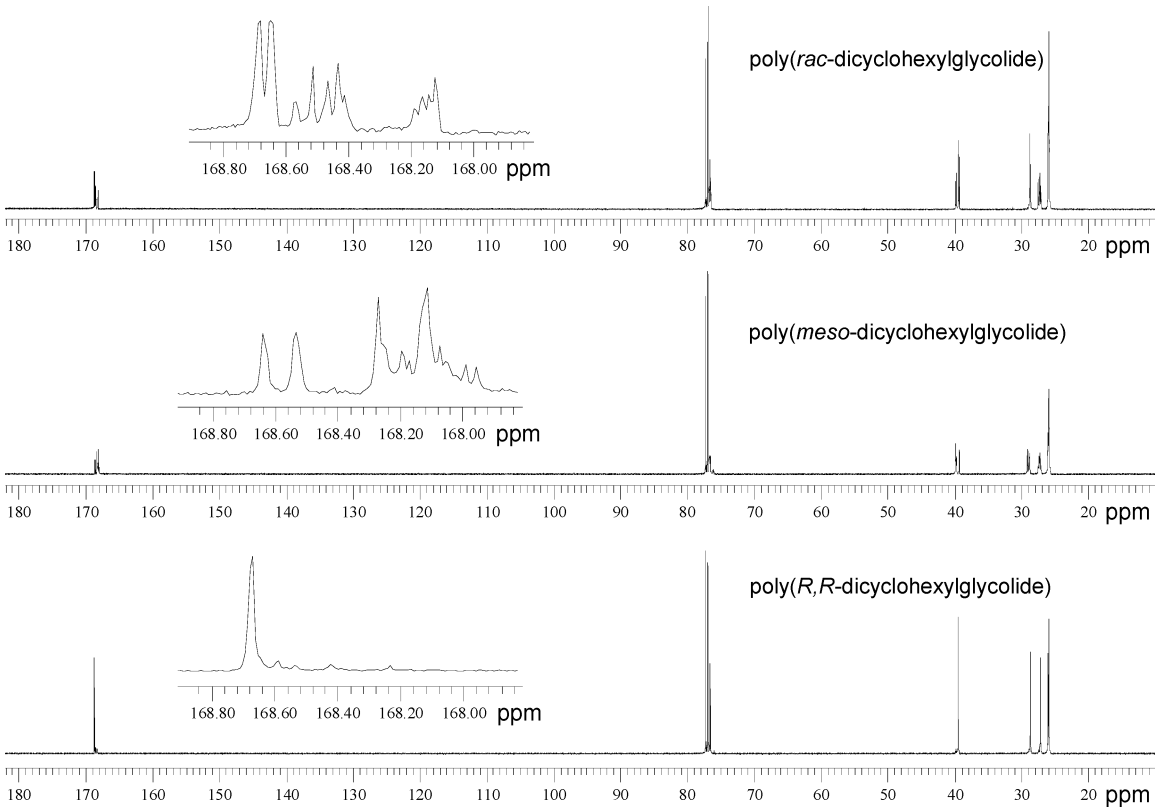


Figure 9. 125 MHz ^{13}C NMR spectra for poly(*rac*-dicyclohexylglycolide), poly(*meso*-dicyclohexylglycolide), and poly(*R,R*-dicyclohexylglycolide).

the consequences of stereoregularity in dicyclohexylglycolides, *meso*- and *R,R*-dicyclohexylglycolides were isolated and polymerized. Because the kinetic data suggested a high degree of alternation, having the NMR spectra of *meso*-poly(dicyclohexylglycolide) would simplify identification of meso stereochemical defects in poly(*R,R*-dicyclohexylglycolide). Access to *R,R*-dicyclohexylglycolides is straightforward because (*R*)-(−)-mandelic acid can be hydrogenated directly to (*R*)-(−)-2-cyclohexyl-2-hydroxyacetic acid with retention of configuration. The low melting *meso*-dicyclohexylglycolide was polymerized at 130 °C, while the higher melting *R,R*-dicyclohexylglycolide required heating to 200 °C, the same conditions used for the

polymerization of *rac*-dicyclohexylglycolide. The glass transition temperatures and molecular weights are listed in Table 2. The DSC traces are shown in Figure S3 (Supporting Information). The meso and racemic polymers have T_g's of ~98 °C, but the T_g of poly(*R*,*R*-dicyclohexylglycolide) was noticeably higher, 104 °C. The *R*,*R* polymer has a specific rotation $[\alpha]^{20}_D = +23.0°$ ($c = 1.0$, $CHCl_3$). However, DSC scans and polarized optical microscopy studies of poly(*R*,*R*-dicyclohexylglycolide) samples showed no signs of crystallinity.

The degree of crystallinity in poly(L-lactide) is largely controlled by the presence of meso and D-lactide impurities,[7] which can be detected by ^{1}H and ^{13}C NMR. The ^{1}H NMR and ^{13}C NMR spectra of *rac*-, *meso*-, and *R*,*R*-poly(dicyclohexylglycolide)s are shown in Figures 8 and 9. An examination of the methine region in the ^{1}H NMR suggests a high degree of stereoregularity for *R*,*R*-poly(dicyclohexylglycolide). However, a comparison with the spectrum of poly(*meso*-dicyclohexylglycolide) suggests that the small signals at 5.16 and 5.05 ppm correspond to contamination from meso dyads. The ^{13}C NMR spectrum of poly(*R*,*R*-dicyclohexylglycolide) is consistent with the ^{1}H NMR data. The ^{13}C NMR spectrum is dominated by a singlet at 168.7 ppm, confirming the overall isotactic nature of the polymer, but it too shows minor resonances that imply a population of meso dyads. Integration of the carbonyl region places the isotactic content at 86%. Because the *R*,*R* monomer used in these polymerizations was >99% pure, we suspect that epimerization occurs during polymerization. To confirm this notion, we carried out a solution polymerization of the same monomer at 90 °C. Integration of the carbonyl region in the ^{13}C NMR confirmed increased stereoregularity, with the isotactic resonance corresponding to 98% of the total carbonyl intensity (Figure S4). While the T_g increased to 104 °C, no crystallinity was detected via XRD, DSC, and polarized optical microscopy.

Conclusions

Polylactides substituted with cyclohexyl and isopropyl groups were synthesized by ring-opening polymerization of the substituted glycolides using Sn(2-ethylhexanoate)$_2$ as a catalyst and 4-*tert*-butylbenzyl alcohol as initiator. For *rac*-dicyclohexylglycolide polymer, the T_g is 44 °C higher than that of poly(*rac*-lactide); even the less sterically demanding poly(*rac*-methylcyclohexylglycolide) has a T_g of 73 °C. These high T_g's are derived from the stiffening of the polymer backbones caused by the bulky cyclohexyl groups. Solution polymerizations were used to probe the steric effects of cyclohexyl, isopropyl, and methyl substitution. The steric hindrance follows the expected order (cyclohexyl > isopropyl > methyl), but the isopropyl derivative had the lowest T_g.

The effects of stereoregularity on polymer properties were studied. Polymerization of optically pure *R*,*R*-dicyclohexylglycolide yielded an optically active polymer, poly(*R*,*R*-dicyclohexylglycolide), with a high T_g (104 °C). However, no crystallinity was detected via XRD, DSC, and polarized optical microscopy. Poly(*rac*-dicyclohexylglycolide) and poly(*meso*-dicyclohexylglycolide) have very similar thermal properties, but NMR shows they have quite different stereosequence distributions, implying that, as compared to polylactide, the stereosequence distribution is a less important factor in determining poly(dicyclohexylglycolide)'s properties.

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Supporting Information Available: 500 MHz ^{1}H NMR spectrum of poly(*rac*-methylcyclohexylglycolide) (Figure S1), DSC traces of substituted polyglycolides (Figure S2) and poly(dicyclohexylglycolide)s (Figure S3), rheological properties of poly(dicyclohexylglycolide) (Figure S4), and ^{13}C NMR spectra of the carbonyl region for solution polymerized *R*,*R*-dicyclohexylglycolide (Figure S5). This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Albertsson, A. C.; Varma, I. K. *Biomacromolecules* **2003**, *4*, 1466.
(2) Dechy-Cabaret, O.; Martin-Vaca, B.; Bourissou, D. *Chem. Rev.* **2004**, *104*, 6147−6176.
(3) Ikada, Y.; Tsuji, H. *Macromol. Rapid Commun.* **2000**, *21*, 117−132.
(4) Lou, X. D.; Detrembleur, C.; Jerome, R. *Macromol. Rapid Commun.* **2003**, *24*, 161−172.
(5) Mecking, S. *Angew. Chem., Int. Ed.* **2004**, *43*, 1078−1085.
(6) Auras, R.; Harte, B.; Selke, S. *Macromol. Biosci.* **2004**, *4*, 835−864.
(7) Drumright, R. E.; Gruber, P. R.; Henton, D. E. *Adv. Mater.* **2000**, *12*, 1841−1846.
(8) Chiellini, E.; Solaro, R. *Adv. Mater.* **1996**, *8*, 305−313.
(9) Hu, Y.; Rogunova, M.; Topolkaraev, V.; Hiltner, A.; Baer, E. *Polymer* **2003**, *44*, 5701−5710.
(10) Ouchi, T.; Minari, T.; Ohya, Y. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 5482−5487.
(11) Ovitt, T. M.; Coates, G. W. *J. Am. Chem. Soc.* **2002**, *124*, 1316−1326.
(12) Zhong, Z. Y.; Dijkstra, P. J.; Feijen, J. *J. Am. Chem. Soc.* **2003**, *125*, 11291−11298.
(13) Cheng, M.; Attygalle, A. B.; Lobkovsky, E. B.; Coates, G. W. *J. Am. Chem. Soc.* **1999**, *121*, 11583−11584.
(14) Abe, H.; Doi, Y.; Hori, Y.; Hagiwara, T. *Polymer* **1998**, *39*, 59−67.
(15) Albertsson, A. C.; Lofgren, A. *J. Macromol. Sci., Pure Appl. Chem.* **1995**, *A32*, 41.
(16) Buchholz, B. *J. Mater. Sci.: Mater. Med.* **1993**, *4*, 381.
(17) Cai, Q.; Bei, J. Z.; Wang, S. G. *Polym. Adv. Technol.* **2002**, *13*, 105−111.
(18) Chen, X. H.; McCarthy, S. P.; Gross, R. A. *Macromolecules* **1998**, *31*, 662−668.
(19) Feng, Y.; Klee, D.; Hocker, H. *Macromol. Biosci.* **2004**, *4*, 587−590.
(20) Grijpma, D. W.; Pennings, A. J. *Macromol. Chem. Phys.* **1994**, *195*, 1633.
(21) Matsumura, S.; Tsukada, K.; Toshima, K. *Int. J. Biol. Macromol.* **1999**, *25*, 161.
(22) Pego, A. P.; Poot, A. A.; Grijpma, D. W.; Feijen, J. *J. Mater. Sci.: Mater. Med.* **2003**, *14*, 767−773.
(23) Ruckenstein, E.; Yuan, Y. M. *J. Appl. Polym. Sci.* **1998**, *69*, 1429−1434.
(24) Schmidt, P.; Keul, H.; Hocker, H. *Macromolecules* **1996**, *29*, 3674.
(25) Shirahama, H.; Mizuma, K.; Umemoto, K.; Yasuda, H. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 1374.
(26) Zhu, K. J.; Lei, Y. A. *Polym. Int.* **1997**, *43*, 210−216.
(27) Zhu, K. J.; Lin, X. Z.; Yang, S. L. *J. Appl. Polym. Sci.* **1990**, *39*, 1−9.
(28) Tasaka, F.; Ohya, Y.; Ouchi, T. *Macromolecules* **2001**, *34*, 5494−5500.
(29) Gadzinowski, M.; Sosnowski, S. *J. Polym. Sci., Part A: Polym. Chem.* **2003**, *41*, 3750−3760.
(30) Ikada, Y.; Jamshidi, K.; Tsuji, H.; Hyon, S. H. *Macromolecules* **1987**, *20*, 904−906.
(31) Radano, C. P.; Baker, G. L.; Smith, M. R. *J. Am. Chem. Soc.* **2000**, *122*, 1552−1553.
(32) Yin, M.; Baker, G. L. *Macromolecules* **1999**, *32*, 7711−7718.
(33) Simmons, T. L.; Baker, G. L. *Biomacromolecules* **2001**, *2*, 658−663.
(34) Trimaille, T.; Moller, M.; Gurny, R. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4379.
(35) Liu, T. Q.; Simmons, T. L.; Bohnsack, D. A.; Mackay, M. E.; Smith, M. R.; Baker, G. L. *Macromolecules* **2007**, *40*, 6040−6047.
(36) Du, F. S.; Ye, W. P.; Gu, Z. W.; Yang, J. Y. *J. Appl. Polym. Sci.* **1997**, *63*, 643−650.
(37) Gerhardt, W. W.; Noga, D. E.; Hardcastle, K. I.; Garcia, A. J.; Collard, D. M.; Weck, M. *Biomacromolecules* **2006**, *7*, 1735.
(38) He, B.; Bei, J. Z.; Wang, S. G. *Polymer* **2003**, *44*, 989−994.
(39) Kimura, Y.; Shirotani, K.; Yamane, H.; Kitao, T. *Polymer* **1993**, *34*, 1741.

(40) Leemhuis, M.; van Nostrum, C. F.; Kruijtzer, J. A. W.; Zhong, Z. Y.; ten Breteler, M. R.; Dijkstra, P. J.; Feijen, J.; Hennink, W. E. *Macromolecules* **2006**, *39*, 3500−3508.
(41) Veld, P.; Dijkstra, P. J.; Feijen, J. *Macromol. Chem. Phys.* **1992**, *193*, 2713.
(42) Wang, L. A.; Ha, X. H.; Yuan, Z. *Polymer* **2006**, *47*, 6978.
(43) Yang, J. Y.; Yu, J.; Li, M.; Pan, H. Z.; Gu, Z. W.; Cao, W. X.; Feng, X. D. *Acta Chim. Sin.* **2001**, *59*, 1809−1812.
(44) Nijenhuis, A. J.; Grijpma, D. W.; Pennings, A. J. *Polymer* **1996**, *37*, 2783−2791.
(45) Satoh, T.; Onda, K.; Yamakawa, K. *J. Org. Chem.* **1991**, *56*, 4129−4134.
(46) Aggarwal, V. K.; Thomas, A.; Schade, S. *Tetrahedron* **1997**, *53*, 16213−16228.
(47) Riley, D. P.; Shumate, R. E. *J. Org. Chem.* **1980**, *45*, 5187−5193.
(48) Stocker, J. H. *J. Org. Chem.* **1962**, *27*, 2288−&.
(49) Mori, K.; Takaishi, H. *Tetrahedron* **1989**, *45*, 1639−1646.
(50) Baker, G. L.; Smith, M. R., III. U.S. Patent 6,469,133, 2002.
(51) Witzke, D. R.; Narayan, R.; Kolstad, J. J. *Macromolecules* **1997**, *30*, 7075−7085.
(52) Kowalski, A.; Duda, A.; Penczek, S. *Macromolecules* **2000**, *33*, 7359−7370.
(53) Zhong, Z. Y.; Dijkstra, P. J.; Jan, F. J.; Kwon, Y. M.; Bae, Y. H.; Kim, S. W. *Macromol. Chem. Phys.* **2002**, *203*, 1797−1803.
(54) Trimaille, T.; Gurny, R.; Moller, M. *J. Biomed. Mater. Res., Part A* **2007**, *80A*, 55.
(55) Benabdillah, K. M.; Coudane, J.; Boustta, M.; Engel, R.; Vert, M. *Macromolecules* **1999**, *32*, 8774.
(56) Nishida, H.; Mori, T.; Hoshihara, S.; Fan, Y. J.; Shirai, Y.; Endo, T. *Polym. Degrad. Stab.* **2003**, *81*, 515−523.
(57) Zhang, J. M.; Sato, H.; Tsuji, H.; Noda, I.; Ozaki, Y. *Macromolecules* **2005**, *38*, 1822−1828.
(58) Cao, C. Z.; Lin, Y. B. *J. Chem. Inf. Comput. Sci.* **2003**, *43*, 643−650.
(59) Zhao, J.; Hahn, S. F.; Hucul, D. A.; Meunier, D. M. *Macromolecules* **2001**, *34*, 1737−1741.
(60) Zell, M. T.; Padden, B. E.; Paterick, A. J.; Thakur, K. A. M.; Kean, R. T.; Hillmyer, M. A.; Munson, E. J. *Macromolecules* **2002**, *35*, 7700−7707.
(61) Chisholm, M. H.; Iyer, S. S.; McCollum, D. G.; Pagel, M.; Werner-Zwanziger, U. *Macromolecules* **1999**, *32*, 963−973.
(62) Coudane, J.; UstarizPeyret, C.; Schwach, G.; Vert, M. *J. Polym. Sci., Part A: Polym. Chem.* **1997**, *35*, 1651−1658.
(63) Kasperczyk, J. E. *Polymer* **1999**, *40*, 5455−5458.
(64) Thakur, K. A. M.; Kean, R. T.; Hall, E. S.; Kolstad, J. J.; Lindgren, T. A.; Doscotch, M. A.; Siepmann, J. I.; Munson, E. J. *Macromolecules* **1997**, *30*, 2422−2428.
(65) Thakur, K. A. M.; Kean, R. T.; Hall, E. S.; Kolstad, J. J.; Munson, E. J. *Macromolecules* **1998**, *31*, 1487−1494.

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