

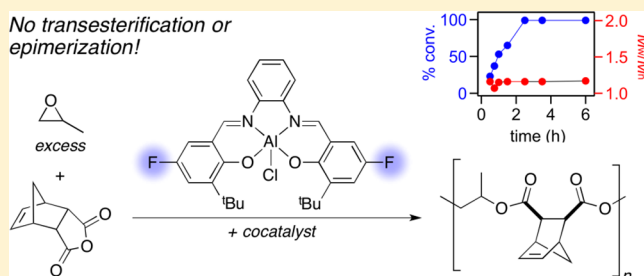
# Electronic Effects of Aluminum Complexes in the Copolymerization of Propylene Oxide with Tricyclic Anhydrides: Access to Well-Defined, Functionalizable Aliphatic Polyesters

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**S** Supporting Information

**ABSTRACT:** The synthesis of well-defined and functionalizable aliphatic polyesters remains a key challenge in the advancement of emerging drug delivery and self-assembly technologies. Herein, we investigate the factors that influence the rates of undesirable transesterification and epimerization side reactions at high conversion in the copolymerization of tricyclic anhydrides with excess propylene oxide using aluminum salen catalysts. The structure of the tricyclic anhydride, the molar ratio of the aluminum catalyst to the nucleophilic cocatalyst, and the Lewis acidity of the aluminum catalyst all influence the rates of these side reactions. Optimal catalytic activity and selectivity against these side reactions requires a careful balance of all these factors. Effective suppression of undesirable transesterification and epimerization was achieved even with sterically unhindered monomers using a fluorinated aluminum salen complex with a substoichiometric amount of a nucleophilic cocatalyst. This process can be used to synthesize well-defined block copolymers via a sequential addition strategy.



## INTRODUCTION

Aliphatic polyesters are important alternatives to petroleum-based materials<sup>1</sup> because they can be produced using renewable feedstocks and disposed of with minimal environmental impact.<sup>2</sup> Current commercial aliphatic polyesters, such as polylactide and polycaprolactone, are used in applications ranging from biomedical devices<sup>3</sup> to consumer products, such as polyurethane foams<sup>4</sup> and packaging materials.<sup>5</sup> However, the applicability of current aliphatic polyesters in emerging drug delivery and self-assembly technologies is limited because of their hydrophobicity, semicrystallinity, and lack of functionality. A promising approach to address these deficiencies is the development of functionalizable aliphatic polyester copolymers that would allow for facile tuning of physical properties and functionality via postpolymerization modification. Most recent examples<sup>2,8</sup> are based on the ring-opening polymerization (ROP) of functionalizable lactones<sup>6</sup> and glycolide derivatives.<sup>7</sup> This strategy unfortunately has several disadvantages. Notably, functional lactones require multiple synthetic steps to make, and the production of well-defined polymers at high monomer conversion is precluded by transesterification side reactions.

An alternative route to aliphatic polyesters is the alternating copolymerization of epoxides with cyclic anhydrides (Scheme 1a).<sup>8</sup> Our group and others have reported zinc,<sup>9</sup> aluminum,<sup>10</sup> chromium,<sup>10c–i,11</sup> cobalt,<sup>10c–i,12</sup> manganese,<sup>10d,f,g,13</sup> iron,<sup>13a</sup> and magnesium<sup>9g</sup> complexes that produce highly alternating copolymers. The metal complex serves as a Lewis acid that activates the epoxide for ring-opening, and, in the case of metal salen- and porphyrin-based catalysts, the addition of an onium salt such as tetrabutylammonium chloride or bis-

(triphenylphosphine)iminium chloride (PPNCl) is required to achieve high catalytic activity. The key advantage of this process over the ROP of lactones for synthesizing functionalizable aliphatic polyesters is the large number and diversity of functional monomers that are either commercially available or easily synthesized.

Unfortunately, current catalysts undergo undesirable side reactions at high monomer conversion especially in the presence of excess epoxide (Scheme 1b). Inoue,<sup>10a,b</sup> Chisholm,<sup>10h,11c</sup> and Nozaki<sup>13a</sup> noted that metal porphyrin and corrole complexes homopolymerize epoxides when the copolymerization is run to full conversion with excess epoxide. Duchateau and co-workers<sup>11a</sup> observed that chromium salen and porphyrin catalysts form cyclic polymers via intramolecular transesterification based on MALDI-TOF-MS analyses. Our group<sup>10i</sup> also found that chromium and cobalt salen catalysts undergo transesterification and epimerization side reactions when copolymerizing an excess of propylene oxide (PO) with the Diels–Alder adduct of maleic anhydride and  $\alpha$ -terpinene (**1a**). These side reactions result in mixtures of polymer architectures and microstructures that can be detrimental to the bulk properties of the resulting material.

There are many practical advantages to running polymerizations to full conversion with an excess of a volatile epoxide such as PO if side reactions can be eliminated. First, because the polymerization rate depends on the concentration of epoxide,<sup>11b</sup> the polymerization proceeds under pseudo-zero-order kinetics,

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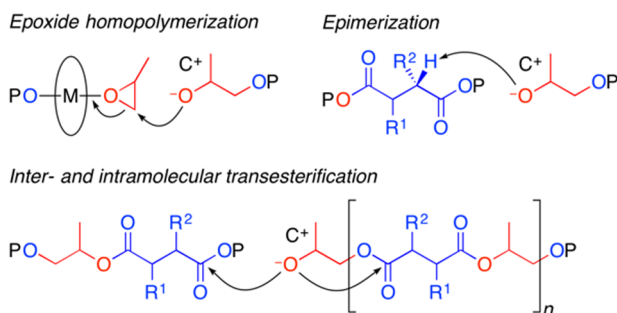
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### Scheme 1. Synthesis of Aliphatic Polyesters via Alternating Ring-Opening Copolymerization and Common Side Reactions<sup>a</sup>

#### a) Alternating copolymerization of propylene oxide with cyclic anhydrides



#### b) Side reactions commonly observed at the end of the copolymerization



<sup>a</sup>P = polymer, M = metal center, C<sup>+</sup> = counteraction.

resulting in no appreciable decrease in the rate of polymerization as a function of conversion. In addition, excess epoxide may be easily recovered and reused via distillation of the crude polymerization mixture,<sup>14</sup> and well-defined block copolymers can be synthesized.

We recently discovered that (salph)AlCl [**2a**, salph = *N,N'*-bis(3,5-*tert*-butylsalicylidene)-1,2-diaminobenzene] and PPNCI copolymerize **1a** and PO with perfect alternation and minimal side reactions even when the copolymerization is run to full conversion with excess PO.<sup>10i</sup> This aliphatic polyester and related copolymers derived from other tricyclic anhydrides are highly interesting because they exhibit unique properties compared to commercial aliphatic polyesters. They are

amorphous, have higher glass transitions than polylactide ( $T_g > 60\text{ }^\circ\text{C}$ ),<sup>10i</sup> and can be readily functionalized through thiol–ene click chemistry.<sup>11f,15</sup> Herein, we investigate the factors that influence the rates of undesirable side reactions at high conversion in the copolymerization of tricyclic anhydrides with excess PO. We report an optimized process that utilizes a fluorinated salph aluminum complex to produce a variety of well-defined, functionalizable aliphatic polyesters.

## RESULTS AND DISCUSSION

The cyclic anhydrides **1a**, **1b**, **1c**, and **1e** were synthesized via Diels–Alder reactions as previously described, and monomer **1d** was prepared by catalytic hydrogenation of **1c** (Table 1). Cyclic anhydrides **1b–e** were copolymerized with an excess of PO using **2a** and PPNCI under conditions that were previously found to be optimal for the copolymerization of **1a** with PO.<sup>10i</sup> When the copolymerizations were quenched before full conversion, all resulting copolymers are perfectly alternating and have narrow molecular weight distributions ( $M_w/M_n < 1.20$ ). The *cis* stereochemistry of each monomer is also retained in the corresponding polymers (Table 1,  $t_{\text{rxn}} \leq 60$  min).<sup>16</sup> The turnover frequencies (TOFs) observed for **1b–e** (TOF = 95–185 h<sup>-1</sup>, entries 2–5,  $t_{\text{rxn}} \leq 40$  min) are higher than the one observed with the bulkier monomer **1a** (TOF = 63 h<sup>-1</sup>, entry 1,  $t_{\text{rxn}} = 60$  min).

Although minimal transesterification and epimerization are observed in polymerizations with **1a** at high conversion (entry 1,  $t_{\text{rxn}} = 150$  min), polymerizations with **1b–d** at high conversion yield polymers with broad molecular weight distributions ( $M_w/M_n = 1.64–1.69$ ) and significant amounts of *trans*-diester linkages (Table 1, entries 2–4,  $t_{\text{rxn}} = 150$  min).<sup>17</sup> These copolymers are likely more susceptible to transesterification and epimerization compared to poly(**1a-*alt***-PO) because of the decreased steric bulk along the polymer chain. However, no polyether linkages were observed by <sup>1</sup>H or <sup>13</sup>C NMR spectroscopy. The polymerization with **1e** surprisingly yields a well-defined copolymer even at high monomer conversion. The resulting poly(**1e-*alt***-PO) has an  $M_n$  of 8.8 kDa, an  $M_w/M_n$  of 1.15, and a % *cis*-diester content of 97%. The  $\alpha$ -methyl groups along poly(**1e-*alt***-PO) sterically hinder the *exo*-face of the diester

**Table 1. Effect of Cyclic Anhydride Structure on Turnover Frequency in Copolymerizations with PO Using **2a** and PPNCI (PPNCI = [Ph<sub>3</sub>P–N=PPh<sub>3</sub>]Cl)<sup>a</sup>**

entry	anhyd.	short reaction time ( $t_{\text{rxn}} \leq 60$ min)							long reaction time ( $t_{\text{rxn}} = 150$ min)			
		$t_{\text{rxn}}$ (min)	conv (%) <sup>b</sup>	TOF (h <sup>-1</sup> ) <sup>c</sup>	$M_n$ (kDa) <sup>d</sup>	$M_w/M_n$ <sup>d</sup>	% <i>cis</i> <sup>e</sup>	conv (%) <sup>b</sup>	$M_n$ (kDa) <sup>d</sup>	$M_w/M_n$ <sup>d</sup>	% <i>cis</i> <sup>e</sup>	
1 <sup>f</sup>	<b>1a</b>	60	63	63	7.4	1.11	>99	>99	10.2	1.16	97	
2	<b>1b</b>	35	71	122	6.4	1.13	>99	>99	11.5	1.64	48	
3	<b>1c</b>	40	63	95	6.0	1.14	>99	>99	13.7	1.65	58	
4	<b>1d</b>	30	76	152	6.2	1.18	>99	>99	11.7	1.69	25	
5	<b>1e</b>	26	80	185	7.2	1.14	>99	>99	8.8	1.15	97	

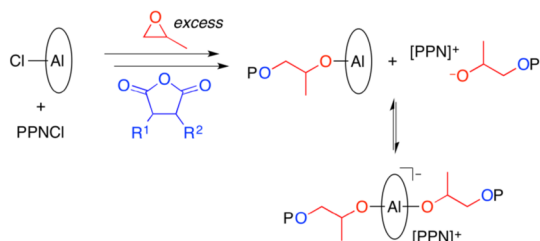
<sup>a</sup>[PO]:[**1**]:[**2a**]:[PPNCI] = 500:100:1:1. <sup>b</sup>Conversion of cyclic anhydride, determined by <sup>1</sup>H NMR spectroscopy. <sup>c</sup>TOF = Turnover frequency, mol **1** consumed · mol **2a**<sup>-1</sup> · h<sup>-1</sup>. <sup>d</sup>Determined by GPC in THF, calibrated with polystyrene standards. <sup>e</sup>Determined by <sup>13</sup>C NMR spectroscopy. <sup>f</sup>ref 10i.

units, which evidently decreases the rate of transesterification and epimerization.

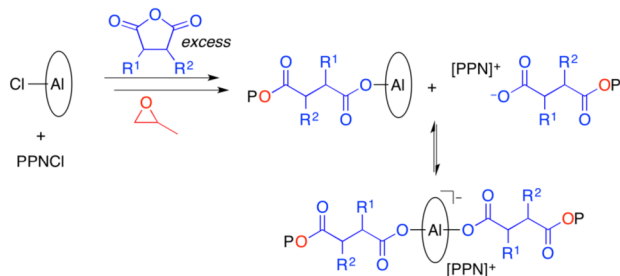
On the basis of the mechanisms proposed by Inoue<sup>10a,b</sup> and Chisholm,<sup>10h,11c</sup> the identity of the catalytic species at the end of the copolymerization depends on  $[\text{PO}]/[\mathbf{1}]$ . When the copolymerization is performed with an excess of PO, the resulting species after consumption of the cyclic anhydride likely consist of an aluminum salen alkoxide and a  $[\text{PPN}]^+$  alkoxide, which are in equilibrium with a hexacoordinate dialkoxide aluminate species (Scheme 2a). Conversely, with an excess of

**Scheme 2. Proposed Equilibria at the End of the Copolymerization When Using (a) an Excess of Epoxide and (b) an Excess of Cyclic Anhydride<sup>a</sup>**

a) End of the copolymerization with excess epoxide



b) End of the copolymerization with excess cyclic anhydride



<sup>a</sup>P = polymer, PPNCI =  $[\text{Ph}_3\text{P}-\text{N}=\text{PPh}_3]\text{Cl}$ .

cyclic anhydride, the resulting species after all of the epoxide is consumed are likely an aluminum salen carboxylate and a  $[\text{PPN}]^+$  carboxylate, which are in equilibrium with a hexacoordinate dicarboxylate aluminate complex (Scheme 2b).

We hypothesized that  $[\text{PPN}]^+$  alkoxides are largely responsible for the observed transesterification and epimerization side reactions because they are the most highly basic and nucleophilic species present at the end of the copolymerization. By contrast, epimerization is not observed when using an excess of cyclic anhydride because the  $[\text{PPN}]^+$  carboxylates formed at the end of the copolymerization are considerably less basic than  $[\text{PPN}]^+$  alkoxides. Transesterification is also not observed in this case because it is thermodynamically unfavorable for carboxylates to undergo transesterification with the main chain ester bonds.

We thus sought to compensate for the reduced steric bulk of the copolymers based on **1b–d** by modulating the reactivity of the species at the end of the copolymerization without destroying the activity of the catalyst. We first investigated the effect of changing  $[\text{PPNCI}]/[\mathbf{2}]$  on the degree of transesterification and epimerization after reaching full conversion of **1c** using an excess of PO. If  $[\text{PPN}]^+$  alkoxides are primarily responsible for the side reactions, then these side reactions may be suppressed by using an excess of **2a** to drive the equilibrium toward the presumably less reactive dialkoxide aluminum complex (Scheme 2a).

Monomer **1c** was used as a model monomer because it is inexpensive and the resulting polymers are easily functionalized.<sup>11f,15</sup> Copolymerizations were performed under similar conditions as described in Table 1 using 0.5, 0.9, and 1.1 equiv of PPNCI. Turnover frequencies (TOFs) were determined by quenching before reaching full conversion (Table 2,  $t_{\text{rxn}} = 25$  min). TOFs increased as more PPNCI was used. For example, use of 0.5 equiv of PPNCI resulted in a TOF of  $36 \text{ h}^{-1}$  (entry 1,  $t_{\text{rxn}} = 25$  min), while use of 0.9 and 1.1 equiv of PPNCI resulted in TOFs of 92 and  $106 \text{ h}^{-1}$ , respectively (entries 2 and 3,  $t_{\text{rxn}} = 25$  min). These results are in contrast to previous work by Chisholm<sup>10h,11c</sup> and Darensbourg,<sup>11b</sup> who both reported that variation of the ratio of PPNCI to metal complex did not significantly affect the initial rate of copolymerization for comparable catalytic systems. We could not detect any *trans*-diester linkages by <sup>13</sup>C NMR spectroscopy for any loading of PPNCI investigated when the copolymerization was quenched before reaching full conversion.

A similar series of polymerizations were performed but quenched approximately 2 h after reaching full conversion of **1c**. The ratio  $[\text{PPNCI}]/[\mathbf{2a}]$  has a strong effect on the rate of transesterification and epimerization, although no PO homopolymerization was observed in any case. Polymerizations using

**Table 2. Variation of the Loading of PPNCI in the Copolymerization of 1a with PO using 2a<sup>a</sup>**

entry	$[\text{PPNCI}]/[\mathbf{2a}]$	short reaction time ( $t_{\text{rxn}} = 25$ min)					long reaction time ( $t_{\text{rxn}} \geq 180$ min)				
		conv (%) <sup>b</sup>	TOF ( $\text{h}^{-1}$ ) <sup>c</sup>	$M_n$ (kDa) <sup>d</sup>	$M_w/M_n$ <sup>d</sup>	% <i>cis</i> <sup>e</sup>	$t_{\text{rxn}}$ (min)	conv (%) <sup>b</sup>	$M_n$ (kDa) <sup>d</sup>	$M_w/M_n$ <sup>d</sup>	% <i>cis</i> <sup>e</sup>
1	0.5	15	36	n.d. <sup>f</sup>	n.d. <sup>f</sup>	>99	300	>99	8.1	1.46	88
2	0.9	39	92	3.5	1.16	>99	180	>99	7.5	1.66	64
3	1.1	44	106	3.7	1.18	>99	180	>99	9.8	1.64	50

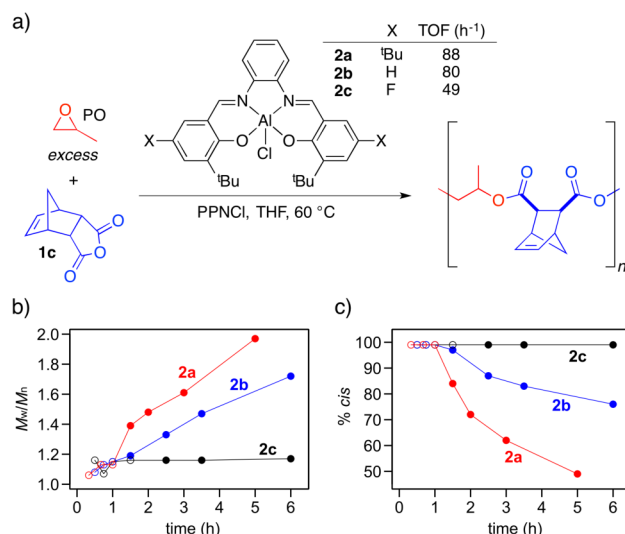
<sup>a</sup> $[\text{PO}]:[\mathbf{1}]:[\mathbf{2a}] = 500:100:1$ . <sup>b</sup>Conversion of cyclic anhydride, determined by <sup>1</sup>H NMR spectroscopy. <sup>c</sup>TOF = Turnover frequency, mol **1** consumed  $\cdot \text{mol } \mathbf{2a}^{-1} \cdot \text{h}^{-1}$ . <sup>d</sup>Determined by GPC in THF, calibrated with polystyrene standards. <sup>e</sup>Determined by <sup>13</sup>C NMR spectroscopy. <sup>f</sup>ref 10i.



0.9 and 1.1 equiv of PPNCl (entries 2 and 3,  $t_{\text{rxn}} = 180$  min) yield polymers with similarly broad molecular weight distributions (1.66 and 1.64, respectively), although poly(**1c-alt-PO**) produced using 0.9 equiv has significantly more *cis*-diester linkages than the polymer produced using 1.1 equiv (64 vs 50% *cis*, respectively). Improved selectivity against transesterification and epimerization is realized when  $[\text{PPNCl}]/[\mathbf{2a}]$  is reduced to 0.5, as the resulting poly(**1c-alt-PO**) has an  $M_w/M_n$  of 1.46 and 88% *cis*-diester linkages (entry 1,  $t_{\text{rxn}} = 300$  min).

While decreasing  $[\text{PPNCl}]/[\mathbf{2a}]$  improves selectivity against side reactions, significant transesterification and epimerization are still observed even when only 0.5 equiv of PPNCl are used. Furthermore, the rate of polymerization is significantly retarded as  $[\text{PPNCl}]/[\mathbf{2a}]$  is decreased. We sought to overcome these issues by further tuning the Lewis acidity of the aluminum catalyst. As suggested in our previous work,<sup>10i</sup> increasing the Lewis acidity of the catalyst causes the equilibrium shown in Scheme 2a to lie more toward the less reactive hexacoordinate aluminate species. We thus synthesized two analogues of **2a** in which we varied the 5-position of the two salicylidene moieties. Complex **2b** is unsubstituted in these positions, and complex **2c** has fluoro substituents (Scheme 3a). We expected that the

**Scheme 3. Copolymerization of PO and **1c** Using **2a–c** and PPNCl<sup>a</sup>**



<sup>a</sup>(a) Effect of catalyst structure on turnover frequency (TOF = turnover frequency, mol **1c** consumed · mol **2**<sup>-1</sup> · h<sup>-1</sup>), see ref 18. (b) Plot of  $M_w/M_n$  versus time. (c) Plot of diester stereochemistry (% *cis*) versus time. (Open circle = copolymerization quenched prior to reaching full conversion of **1c**, based on <sup>1</sup>H NMR spectroscopy).

difference in steric bulk between these substituents would have a negligible effect on catalytic activity because they are distal from the metal center. The ligands were prepared by condensation of the appropriate salicylaldehydes with 1,2-diaminobenzene, and the corresponding aluminum complexes were synthesized in the same way as **2a** to give monometallic complexes. The <sup>1</sup>H and <sup>13</sup>C NMR spectra of each complex were consistent with C<sub>2</sub> symmetry. Complex **2c** exhibits a single resonance at -128.03 ppm in DMSO-*d*<sub>6</sub> by <sup>19</sup>F NMR spectroscopy. All complexes in this study are surprisingly stable to moisture, as NMR spectral analyses were carried out in wet DMSO without degradation.

To compare the degree of transesterification and epimerization observed over time when using each catalyst, we prepared

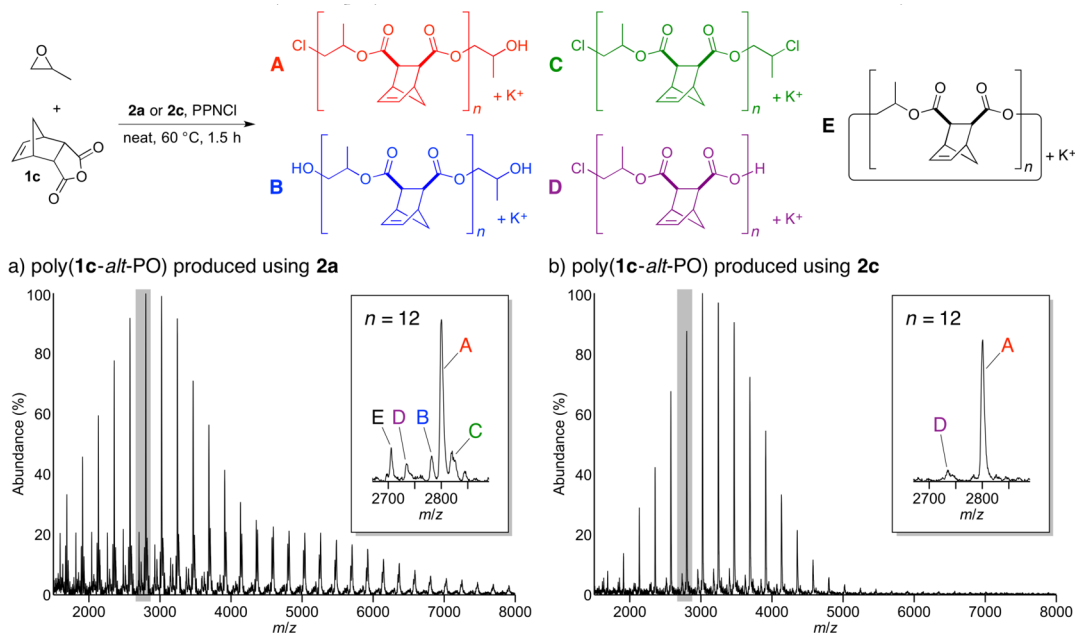
three copolymerizations on 7× scale (8.96 mmol **1c**) using 1.0 equiv of **2a**, **2b**, and **2c**, respectively. Since using a slight excess of the metal complex provides better retention of *cis*-diester stereochemistry and less transesterification as noted above, 0.9 equiv of PPNCl were used. A small amount of THF (1.0 mL) was added to increase the solubility of **1c** in the reaction mixture. Each of these large-scale copolymerizations was evenly divided into 7 separate vials, all of which were run simultaneously and then quenched sequentially at the desired time. This strategy allowed us to easily produce enough poly(**1c-alt-PO**) at each time point to determine the proportion of *cis*-diester linkages by <sup>13</sup>C NMR spectroscopy.

We observed that more electron deficient catalysts exhibit lower rates of polymerization (TOF = 88, 80, and 49 h<sup>-1</sup> for **2a**, **2b**, and **2c**, respectively, Scheme 3a), which is consistent with our previous results.<sup>10i</sup> All three catalysts produce polymers with narrow molecular weight distributions and exclusively *cis*-diester stereochemistry prior to reaching full conversion of **1c** (Scheme 3b and 3c, respectively); **1c** is considerably more reactive than the ester bonds of the polymer chain, likely giving rise to the observed selectivity prior to reaching full conversion.

The electronic properties of the ligands have a dramatic impact on the rates of transesterification and epimerization at high conversion. As expected, polymer formed using **2a** after reaching full conversion exhibits broad molecular weight distributions and low *cis*-diester contents (Scheme 3b and 3c, red traces). Complex **2b** exhibits improved selectivity, as transesterification and epimerization of the resulting polymer proceed at a slower rate than observed when using **2a** (Scheme 3b and 3c, blue traces). No evidence of transesterification or epimerization is observed by GPC and <sup>13</sup>C NMR spectroscopy, respectively, when using the fluorinated complex **2c** even several hours after the copolymerization reaches full conversion (Scheme 3b and 3c, black traces). We attribute the exceptional selectivity of **2c** to its enhanced Lewis acidity and postulate that it shifts the equilibrium depicted in Scheme 2a more toward the less reactive hexacoordinate aluminate complex compared to **2a** and **2b**.<sup>19</sup>

We further compared the selectivity of **2c** to **2a** by performing copolymerizations with high catalyst loading relative to **1c** ( $[\mathbf{1c}]/[\mathbf{2}] = 25$ ) to produce low molecular weight polymers suitable for analysis by MALDI-TOF-MS (Scheme 4). Both polymerizations were run for much longer than it takes to reach full conversion of **1c**. We did not observe any evidence of polyether linkages in either experiment. The MALDI-TOF-MS spectrum of the polymer produced using **2a** (Scheme 4a) revealed the expected  $\alpha$ -Cl, $\omega$ -OH-terminated copolymer (structure A) as the major distribution. Several other minor distributions were also observed, including the  $\alpha$ -OH, $\omega$ -OH-terminated copolymer (structure B), the  $\alpha$ -Cl, $\omega$ -Cl-terminated (structure C), and the  $\alpha$ -Cl, $\omega$ -COOH-terminated copolymer (structure D), as well as the cyclic copolymer (structure E). The presence of these structures is consistent with inter- and intramolecular transesterification. By contrast, the MALDI-TOF-MS spectrum of the polymer produced using **2c** (Scheme 4b) exhibits a major distribution of  $\alpha$ -Cl, $\omega$ -OH-terminated copolymer (structure A) and a minor distribution of  $\alpha$ -Cl, $\omega$ -COOH-terminated copolymer (structure D), suggesting that no significant transesterification takes place under these conditions.

While tuning the Lewis acidity of the catalyst affords excellent suppression of side reactions, this selectivity remains dependent on the ratio  $[\text{PPNCl}]/[\mathbf{2c}]$ . A copolymerization was performed using a slight excess of PPNCl (1.1 equiv) relative to **2c** (1.0 equiv) under the conditions described in entry 3 of Table 2. After

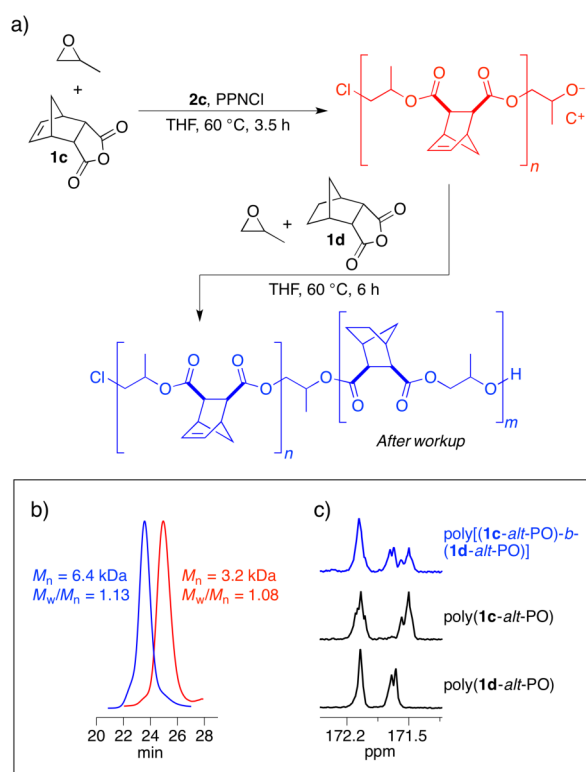
Scheme 4. MALDI-TOF-MS Spectra of Poly(1c-*alt*-PO) Produced Using (a) 2a and (b) 2c<sup>20</sup>

running the copolymerization for 3 h at 60 °C, the resulting copolymer had an  $M_n$  of 10.1 kDa, an  $M_w/M_n$  of 1.24, and a *cis*-diester content of 87%. Although more selective than 2a under these conditions, the use of 2c does not afford perfect selectivity. To achieve both high selectivity against side reactions and a high rate of copolymerization, the ratio of [PPnCl] to [2c] and the Lewis acidity of the catalyst must be carefully balanced.

Finally, to demonstrate the exceptional control of this process, we synthesized a diblock copolymer using 2c (1.0 equiv) and a substoichiometric amount of PPnCl (0.9 equiv., Scheme 5a). The first block was formed by reacting 25 equiv of 1c to full conversion with an excess of PO (125 equiv). A small amount of THF was used for facile transfer of the reaction mixture into the reaction flask used for the copolymerization. The  $M_w/M_n$  of the first block was narrow (1.08), and the  $M_n$  (3.2 kDa) closely corresponded with the theoretical  $M_n$  of 2.9 kDa (Scheme 5b). The next block was produced by adding 1d (25 equiv), PO (125 equiv), and THF to the reaction mixture in one portion. After running to full conversion of 1d, the molecular weight distribution did not significantly broaden ( $M_w/M_n = 1.13$ ), and the  $M_n$  (6.4 kDa) was also close to the theoretical  $M_n$  of 5.9 kDa (Scheme 5b). The <sup>13</sup>C NMR spectrum of the diblock further confirmed its well-defined structure. The carbonyl region was diagnostic, as the diblock exhibits a set of signals that are consistent with a combination of nonepimerized poly(1c-*alt*-PO) and poly(1d-*alt*-PO) (Scheme 5c).

## CONCLUSION

We report the copolymerization of tricyclic anhydrides with an excess of PO using aluminum-based salen complexes and PPnCl. Copolymers derived from tricyclic anhydrides such as 1b–d are more susceptible to transesterification and epimerization than copolymers derived from bulkier monomers such as the terpene-based cyclic anhydride 1a. Using 1c as a model monomer, we found that these side reactions can be suppressed by decreasing the ratio of PPnCl to salen aluminum complex. Elimination of side reactions can be achieved by tuning the Lewis acidity of the aluminum complex; we were unable to detect evidence of

Scheme 5. Synthesis of Poly[(1c-*alt*-PO)-*b*-(1d-*alt*-PO)] via a Sequential Addition Strategy Using 2c and PPnCl<sup>a</sup>

<sup>a</sup>(a) Synthesis of poly[(1c-*alt*-PO)-*b*-(1d-*alt*-PO)]. ( $C^+$  = counter-cation). (b) GPC traces of the first block (in red) and the final diblock copolymer (in blue). (c) Comparison of the carbonyl regions in the <sup>13</sup>C NMR spectra of the diblock copolymer (top trace, in blue), poly(1c-*alt*-PO) (middle trace, from Table 1, entry 3,  $t_{\text{run}} = 40$  min), and poly(1d-*alt*-PO) (bottom trace, Table 1, entry 4,  $t_{\text{run}} = 30$  min).

transesterification or epimerization side reactions when using the fluoro-substituted complex 2c with a substoichiometric amount of PPnCl. We propose that these strategies reduce the

concentration of [PPN]<sup>+</sup> alkoxides at the end of the copolymerization, which we suspect are highly reactive and the cause for the observed side reactions. The exceptional selectivity of **2c** can be used to synthesize well-defined block copolymers. We plan to utilize this process to synthesize functional aliphatic polyester block copolymers and telechelic copolymers.

## ■ ASSOCIATED CONTENT

### ● Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b12888.

Synthetic procedures, raw polymerization data, supplementary experiments, and NMR characterization data. (PDF)

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### Notes

The authors declare no competing financial interest.

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- (16) A detailed discussion regarding the stereochemistry of these polymers can be found in the [Supporting Information](#).
- (17) We observed no degradation of [PPN]<sup>+</sup> under these conditions. Experimental details are reported in the [Supporting Information](#).
- (18) Copolymerizations were performed according to Procedure E in the [Supporting Information](#) with a molar ratio of [PO]:[1c]:[2]:[PPNCI] = 500:100:1:0.9.
- (19) A comparable set of copolymerizations was performed in the absence of THF to rule out significant solvent effects (Table S4, [Supporting Information](#)). Compared to copolymerizations performed with THF as presented in [Scheme 3](#) and Tables S1–S3 ([Supporting](#)

Information), the copolymerization rates with **2a**, **2b**, and **2c** were higher in the absence of THF. The resulting copolymers exhibited similar  $M_w/M_n$  values and % *cis*-diester contents compared to the corresponding copolymers prepared in the presence of THF.

(20) Copolymerizations were performed according to Procedure D in the Supporting Information with a molar ratio of [PO]:[1c]:[2]:[PPNC] = 500:25:1:0.9.