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Aluminum amine-(bis)phenolate complexes for ring-opening polymerization of rac-lactide and ε-caprolactone

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Five aluminum-based amine-bis(phenolate) complexes, three of them novel, with variation of the pendant donor arm were synthesized in excellent yields, and characterized by NMR spectroscopy and X-ray crystallography. The quantitative conversion of the aluminum alkyl species to the corresponding benzyl alkoxide was achieved by the addition of 1 mol eq. of benzyl alcohol, and was confirmed by 1H NMR spectroscopy. The aluminum alkoxides were excellent mediators for the ring-opening polymerization (ROP) of rac-lactide, yielding atactic poly(lactic acid), having excellent correlation between theoretical and calculated molecular weights accompanied by narrow molecular weight distributions. ROP of ε-caprolactone by the aluminum alkoxides showed modest control at 50°C in toluene, but much greater control was achieved when polymerizations were conducted at 25°C, with narrower molecular weight distributions observed in some cases. A relationship between the complex pendant donor arm and the resulting activity in the ROP of both rac-lactide and ε-caprolactone is discussed. Supplementary information is available at http://www.icevirtuallibrary.com/upload/10.1680gmat.12.00006_SupplementaryInformation.pdf

1. Introduction

Catalyst development for ring-opening polymerization (ROP) of lactones has been of particular interest with the goal of accessing biodegradable aliphatic polyesters. These biodegradable polyesters, such as poly(glycolic acid), poly(ε-caprolactone) (PCL), poly(lactic acid) (PLA) and their copolymers, serve as potential alternatives to traditional polymers which are not biodegradable, and are derived from non-renewable petrochemical feedstocks. A significant motivating factor for continuing research of biodegradable aliphatic polyesters is a result of the lactones used in ROP, as glycolide, ε-caprolactone and lactide can be derived from renewable chemical feedstocks. Of these aliphatic polyesters, PLA remains the most popular, as polymer properties can be readily modified through control of the PLA microstructure, as a result of the two stereocentres present in the lactide monomer. Through careful selection of a lactide stereoisomer (DD-, LL-, DL-) and the complex mediating the ROP, the resulting PLA microstructure may be manipulated. This control of PLA properties and its biodegradable nature have sparked much interest in the biomedical industry with PLA-based materials employed as stents, tissue scaffolds and drug delivery vectors. The principle catalyst used to synthesize these materials on an industrial scale has been tin(2-ethylhexanoate) (Sn(Oct)₂),.

As the use of PLA-based biomedical materials in the human body continues to increase, there is a growing desire for organocatalysts and biocompatible metal-based catalysts such as Al, Ca, Mg, and Zn to mediate the ROP. The ideal catalyst would possess similar or higher activity than Sn(Oct)₂, be easily modifiable to fine tune polymer chain microstructure and unavoidable trace metals in the material would be easily metabolized by the body. While all of these...
biocompatible metals have shown quite high activity and phenom-
ena control in ROP of lactide, complexes based on aluminum pro-
vide the control of molecular weight and molecular weight dis-
bution, while frequently inducing extremely high stereoregu-
larity of PLA chains synthesized. Many aluminum-based complexes
have been synthesized using a diverse array of ligand frameworks
containing both nitrogen and oxygen donors. Despite significant
success with a number of metals including lithium,\textsuperscript{15} magnesium,\textsuperscript{16}
lanthanides\textsuperscript{17–27} and group 4\textsuperscript{28,29} amine-\textit{bis}(phenolate) ligands based
on aluminum display significant activity and control in the ROP
of rac-lactide\textsuperscript{30} and ε-caprolactone.\textsuperscript{31,32} This activity and control
of the ROP was achieved with both of these monomers mainly by
alteration of the steric and electron-withdrawing character of aryl
substituents present on the phenolate rings.

In an attempt to further expand the versatility of these catalysts, we
wished to modify the pendant donor arm to observe its effect on
activity and stereoregularity of PLA synthesized by these amine-
\textit{bis}(phenolate) supported Al centres. The amine pendant donor arm
plays an important role in altering the coordination sphere of the Al
centre, and thus we set out to further explore this relationship. With
this in mind, the steric and electronic properties of the donor arm
were manipulated, along with introduction of additional donors sites
(Scheme 1), with particular attention paid to changes in control and
stereoregularity of the ROP of rac-lactide and ε-caprolactone.

2. Results and discussion

Amine-\textit{bis}(phenolate) ligands were prepared by a Mannich
condensation adapted from a literature procedure between 2,4-di-tert-butylphenol, formaldehyde and the desired primary
amine (Scheme 1).\textsuperscript{30} Ligands 1a–e were synthesized in yields rang-
ing from 54%–74%. The appearance of a signal at ~3.5 ppm in
\textsuperscript{1}H NMR spectra corresponding to the Ar-CH$_2$N bridging protons
confirmed the formation of the desired product. Treatment of 1a–e
with 1 equivalent of trimethylaluminum in 10 mL of toluene at
ambient temperature for 24 h allowed access to Al-Me complexes
2a–e in yields from 24%–67%. Disappearance of the phenolic pro-
ton signals at ~10 ppm accompanied by the appearance of a signal
at ~0.55 ppm for Al-CH$_3$ in \textsuperscript{1}H NMR spectra were diagnostic for
successful synthesis 3a–e (Scheme 1).

Single crystals of 2c suitable for X-ray crystallographic analysis were
obtained by slow evaporation of an ether/hexamethyl-
\textit{bis}-siloxane solution (Figure 1). The molecular structure of 2c
determined by X-ray crystallographic analysis reveals a distorted tetrahedral alu-
minum center with O(1)-Al(1)-O(2), O(1)-Al(1)-N(1), O(2)-Al(1)-
N(1), O(1)-Al(1)-C(1), O(2)-Al(1)-C(1), and C(1)-Al(1)-N(1) of
113.20(14)°, 99.05(12)°, 98.14(12)°, 108.43(16)°, 120.54(17)°, and
115.21(16)°, respectively. Bond distances from the aluminum center
to C(1), N(1), O(1), and O(2) are 1.946(4), 1.998(3), 1.736(3), and
1.738(3) Å, respectively. These values resemble those for similar
four-coordinate amine-\textit{bis}(phenolate) aluminum complexes where
the pendant amine functionality does not coordinate to the alumi-
num center.\textsuperscript{33} While the data are of only moderate quality due to
disorder of the di-isopropylamino groups, repeated attempts to
grow better crystals of these catalysts were unsuccessful.

The corresponding benzyl alkoxy species 3a–e were synthesized
directly to avoid inefficient in situ formation of the alkoxy species
during polymerization. Al-Me complexes 2a–e were treated with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{scheme1.png}
\caption{Synthesis of aluminum-alkoxide complexes supported by amine-\textit{bis}(phenolate) frameworks.}
\end{figure}
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2.2 Ring-opening polymerization of ε-caprolactone
A significant difference in activity for ROP of ε-caprolactone was observed when modifications were made to the pendant donor arm of the aluminum complex, 3a and 3b, in which the pendant arm is coordinated to the aluminum center, showed excellent correlation between experimental and theoretical molecular weights accompanied by narrow molecular weight distributions for the resulting PCL. In contrast, 3c–e, produced PCL with broadened molecular weight distributions of 1.36–1.56 at 50°C. Decreasing the polymerization temperature to 25°C, along with a reduction of polymerization time to 30 min, decreased molecular weight distributions drastically for 3d and 3e, with no loss in activity or control (Table 2). However, a significant discrepancy between theoretical and experimental molecular weight was observed for 3d. 3a had significantly lower activity at 25°C compared to polymerizations conducted at 50°C, and 3b produced only trace amounts of PCL at 25°C which is likely caused by inefficient initiation at the lower temperature.

Kinetic studies of 3a and 3b at 50°C in C₆D₆ displayed pseudo-first order kinetics and a linear correlation between molecular weight and percent conversion (Figure 2). Attempts were made to collect kinetic data for 3c and 3e, however, the rate of ROP resulted in nearly quantitative conversion before the first measurement could be taken, even after significant reduction of complex concentration. Kinetic data were collected for 3d at higher percent conversion, but provided no significant insight with regard to any living character present. From these observations, it is clear that the pendant donor arm has a drastic effect on the activity and control in ROP of ε-caprolactone. It is likely that at lower temperatures, the pendant arm of 3d and 3e becomes coordinated to the Al center, thus mimicking the control observed with 3a and 3b. Coordination of the pendant donor arm to the Al center appears crucial in obtaining control in the ROP of ε-caprolactone, and thus future modifications to this ligand framework as well as careful modification of polymerization conditions should be explored. Therefore, it can be concluded that the pendant donor arm plays a more important role in tuning the control these complexes impart in ROP of ε-caprolactone when compared to the ROP of rac-lactide.

2.1 Ring-opening polymerization of rac-lactide
ROP of rac-lactide using aluminum complexes 3a–e was originally screened in toluene at 70°C with a [M]/[Al] of 50, as catalysts 3a and 3b were active under these conditions. However, when this procedure was employed, low activity was observed with only low-molecular weight PLA obtained after workup. Thus, the polymerization conditions were modified by conducting the ROP in molten rac-lactide at 120°C in the absence of solvent. This adjustment proved successful, as at a loading of [M]/[Al] = 100 the ROP of rac-lactide reached higher conversion after 6 h, and was accompanied by narrow molecular weight distributions of <1.20 (Table 1). No loss of control was observed when employing 3a and 3b in the ROP, when compared to polymerizations in solvent. A much greater degree of polymerization was observed for 3c compared to the other complexes, especially 3a. The increased activity is attributed to the lack of a coordinating amine pendant donor in 3c, thus resulting in a more available coordination sphere for an incoming lactide monomer. However, 3b provides the best combination of control and activity compared to the other complexes. This is likely to be due to coordination of the pyridyl pendant donor to the aluminum centre, decreasing its electrophilic character. 3d shows the greatest control of all the complexes examined, and it is speculated that the morpholine pendant donor may play a significant role by controlling the coordination number of the metal centre. 'H NMR studies show significant broadening in the pendant donor resonances, suggesting its fluxional coordination in solution, although thermodynamic parameters of this process were not determined.

3. Experimental
3.1 Materials
All chemicals and solvents were obtained from Sigma Aldrich unless otherwise stated. 99% 2,4-di-tert-butylphenol, formaldehyde, and all primary amines, including N,N-dimethylethylenediamine, 2-(diisopropylamino)ethylamine, 1-(2-aminoethyl)-piperidine, 4-(2-aminoethyl)-morpholine, and 2-(aminomethyl)pyridine were used as received. Trimethylaluminum (2.0 M solution in heptane) was used as obtained. PURASORB dl-lactide was obtained from PURAC Biochem by Gorinchem and sublimed 3 times under vacuum prior to use. ε-Caprolactone was dried over calcium hydride, distilled under inert atmosphere and degassed prior to use. 1a, 1b, 2a, and 2b were synthesized according to literature procedures

Figure 1. Molecular structure of 2e with thermal ellipsoids drawn at 50% probability. Hydrogen atoms and tert-butyl methyl groups have been omitted for clarity.

1 mol equivalent of benzyl alcohol and allowed to stir at ambient temperature for 3 h to afford the benzyl alkoxy species in isolated yields ranging from 27 to 97% after washing with pentane. The 1H NMR spectra of the isolated benzyl alkoxy species showed the disappearance of the singlet at ~0.55 ppm, with a new signal observed at 5.2 ppm, corresponding to Al-CH₂Ph protons. The Al-OBn complexes 3a–e were then used in the ROP of rac-lactide and ε-caprolactone.

2-(diisopropylamino)ethylamine, 1-(2-aminoethyl)-piperidine, and 2-(aminomethyl)pyridine were used as received. Trimethylaluminum (2·0-M solution in heptane) and all primary amines, including N,N-dimethylethylenediamine, 2-(diisopropylamino)ethylamine, 1-(2-aminoethyl)-piperidine, 4-(2-aminoethyl)-morpholine, and 2-(aminomethyl)pyridine were used as received. Trimethylaluminum (2.0 M solution in heptane) was used as obtained. PURASORB dl-lactide was obtained from PURAC Biochem by Gorinchem and sublimed 3 times under vacuum prior to use. ε-Caprolactone was dried over calcium hydride, distilled under inert atmosphere and degassed prior to use. 1a, 1b, 2a, and 2b were synthesized according to literature procedures.

ε-caprolactone, and all primary amines, including N,N-dimethylethylenediamine, 2-(diisopropylamino)ethylamine, 1-(2-aminoethyl)-piperidine, 4-(2-aminoethyl)-morpholine, and 2-(aminomethyl)pyridine were used as received. Trimethylaluminum (2.0 M solution in heptane) was used as obtained. PURASORB dl-lactide was obtained from PURAC Biochem by Gorinchem and sublimed 3 times under vacuum prior to use. ε-Caprolactone was dried over calcium hydride, distilled under inert atmosphere and degassed prior to use. 1a, 1b, 2a, and 2b were synthesized according to literature procedures.
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Table 1. Polymerization of rac-lactide mediated by amine-(bis)phenolate aluminum complexes 3a–e.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Complexa</th>
<th>M_n,th b</th>
<th>M_n c</th>
<th>PDI d</th>
<th>% conversion e</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3a</td>
<td>640</td>
<td>7600</td>
<td>1·19</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>3b</td>
<td>10 700</td>
<td>9500</td>
<td>1·10</td>
<td>74</td>
</tr>
<tr>
<td>3</td>
<td>3c</td>
<td>11 800</td>
<td>10 600</td>
<td>1·18</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>3d</td>
<td>5 700</td>
<td>6 500</td>
<td>1·08</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>3e</td>
<td>9 000</td>
<td>8 500</td>
<td>1·16</td>
<td>62</td>
</tr>
</tbody>
</table>

aPolymerizations conducted at 120°C for 6 h under solvent free conditions with [M]/[Al] = 100.
bCalculated by ([M]/[Al]) × MW(rac-lactide–) × (% conversion) + MW(endgroup).
cCalculated by gel permeation chromatography (size exclusion chromatography) at 50°C in tetrahydrofuran using polystyrene standards (conversion factor = 0·58).
dPDI, polydispersity index.
eCalculated gravimetrically.

Table 2. Polymerization of ε-caprolactone mediated by amine-(bis)phenolate aluminum complexes 3a–e.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Complexa</th>
<th>M_n,th b</th>
<th>M_n c</th>
<th>M_d d</th>
<th>PDI d</th>
<th>% conv. e</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3a</td>
<td>10 100</td>
<td>8 000</td>
<td>1·04</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3b</td>
<td>9 200</td>
<td>10 000</td>
<td>1·20</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3c</td>
<td>8 600</td>
<td>8 900</td>
<td>1·34</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3d</td>
<td>9 400</td>
<td>14 500</td>
<td>1·56</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3e</td>
<td>8 100</td>
<td>6 000</td>
<td>1·32</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3a</td>
<td>4 300</td>
<td>3 400</td>
<td>1·21</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3b</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Trace</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3c</td>
<td>10 900</td>
<td>16 400</td>
<td>1·43</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3d</td>
<td>11 700</td>
<td>6 400</td>
<td>1·20</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3e</td>
<td>10 100</td>
<td>10 600</td>
<td>1·09</td>
<td>89</td>
<td></td>
</tr>
</tbody>
</table>

aPolymerizations conducted at 50°C for 3 h in 5 mL toluene with [M]/[Al] = 100.
bPolymerization conducted at 25°C for 30 min in 5 mL toluene with [M]/[Al] = 100.
cCalculated by ([M]/[Al]) × MW(ε-caprolactone–) × (% conv.) + MW(endgroup).
dCalculated by gel permeation chromatography (size exclusion chromatography) at 50°C in tetrahydrofuran using polystyrene standards (conversion factor = 0·57).
eDetermined gravimetrically.
PDI, polydispersity index.

Toluene, pentane, and ether were obtained from an Innovative Technologies glovebox equipped with an inline Solvent Purification System, consisting of columns of alumina and copper catalyst. The solvents were degassed by three freeze-pump-thaw cycles prior to use. All air-sensitive manipulations were performed in an MBraun LABmaster sp glovebox equipped with a −35°C freezer, (O2) analyzers and a built-in Siemens Simatic Touch Panel or on a dual manifold Schlenk line using standard Schlenk techniques.

1H and 13C NMR spectra were collected on a 300 MHz Burker Avance Spectrometer. Gel permeation chromatography (GPC) analysis was carried out on a Polymer Laboratories PL-GPC 50 Plus integrated GPC system with two 300 × 7·8 mm Jordi Gel DVB mixed bed columns using HPLC grade THF at a flow rate of 1 mL per minute at 50°C, using polystyrene standards for molecular weight determinations. Elemental analyses were conducted by Guelph Analytical Laboratories.

3.2.1 Synthesis of [H2O2NN]1+ (1c)

Adapted from literature procedures,10, 24-di-tert-butylphenol (7·01 g, 34·0 mmol), formaldehyde (3·50 mL, 34·0 mmol) and N,N-disopropylethylendiamine (2·00 mL, 17·0 mmol) was dissolved in 12 mL of methanol. The solution was allowed to reflux at 65°C for 24 h. After 24 h, a yellow precipitate formed. The solution was cooled at −15°C overnight after which the yellow solid was collected via filtration and washed with cold methanol to yield 6·01 g (68%) of [H2O2NN]1+ as a white powder. 1H NMR (300 MHz, CDCl3): δ 8·81 (s, OH, 2H), 7·18 (d, CH-phenoxide, 2H, J = 2 Hz), 6·69 (d, CH-phenoxide, 2H, J = 2 Hz), 3·60 (s, CH2, 4H), 3·26 (sep, CH(CH3)2, 2H, J = 6·6 Hz), 2·79 (t, -N(CH3)2, 2H, J = 6·2 Hz), 2·59 (t, -N(CH3)2, N-, 2H, J = 6·2 Hz), 1·38 (s, C(CH3)2, 18H), 1·27 (s, C(CH3)2, 18H) ppm. 13C NMR (75 MHz, CDCl3): δ 153·1, 140·8, 136·2, 125·1, 123·7, 121·7, 57·1, 56·8, 49·7, 46·7, 35·3, 34·5, 32·1, 30·0, 20·2 ppm. EA found: C 79·2, H 11·0, N 4·8; calculated: C 78·57, H 11·10, N 4·82%.

3.2.2 Synthesis of [H2O2NN]1+ (1d)

Following the procedure outlined for 1c, 2,4-di-tert-butylphenol (7·04 g, 34·0 mmol), formaldehyde (3·50 mL, 34·0 mmol) and 1-(2-aminooethyl)-piperidine (2·50 mL, 17·0 mmol) yielded 5·23 g (54%) of [H2O2NN]1+ as a white powder. 1H NMR (300 MHz, CDCl3): δ 9·62 (s, OH, 2H), 7·20 (d, CH-phenoxide, 2H, J = 2 Hz), 6·89 (d, CH-phenoxide, 2H, J = 2 Hz), 3·57 (s, CH2, 4H), 2·60 (m,
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3.2.3 Synthesis of Al-alkyl complexes
3.3.1 Synthesis of AlMe[O$_2$NN]$_i$Pr ($2c$)
Adapted from a literature procedure,$^{30}$ [H$_2$O$_2$NN]$_i$Pr (4-40 g, 7.50 mmol) and trimethylaluminum (3-00 g, 7.50 mmol) dissolved in 10 mL of toluene was stirred under an inert nitrogen atmosphere for 24 h at ambient temperature. The toluene was removed under reduced pressure and the remaining white residue was washed with 5 mL of pentane, followed by the removal of any remaining volatiles under reduced pressure to yield 2.09 g (45%) of AlMe[O$_2$NN]$_i$Pr as a white powder. $^1$H NMR (300 MHz, CDCl$_3$): δ 7.29 (d, CH$_x$, 2H, J = 2 Hz), 6-89 (d, CH-phenoxide, 2H, J = 2 Hz), 3-91 (m, CH$_y$, 4H, J = 2 Hz), 3-60 (br, CH$_z$, 2H, 2-66 (s, CH$_w$, 4H, 2-54 (s, CH$_v$, 4H, 1-39 (s, C(CH$_h$)$_o$, 18H), 1-27 (s, C(CH$_h$)$_o$, 18H) ppm. $^{13}$C NMR (75 MHz, CDCl$_3$): δ 152-9, 140-8, 136-2, 125-1, 123-7, 121-4, 66-0, 56-4, 55-2, 53-8, 48-2, 35-1, 34-2, 31-9, 29-8 ppm. EA found: C 76-10, H 10-20, N 5-15; calculated: C 76-28, H 10-31, N 4-94%.

3.3.1 Synthesis of AlMe[O2NN]$^m_o$ (1e)
Following the procedure outlined for 1c, 2,4-di-tert-butylphenol (7-03 g, 34-00 mmol), formaldehyde (3-50 mL, 34-00 mmol) and 4-(2-aminoethyl)-morpholine (3-00 mL, 17-00 mmol) yielded 6-72 g (70%) of [H$_2$O$_2$NN]$^m_o$ as a white powder. $^1$H NMR (300 MHz, CDCl$_3$): δ 9-26 (s, OH, 2H), 7-21 (d, CH-phenoxide, 2H, J = 2 Hz), 6-89 (d, CH-phenoxide, 2H, J = 2 Hz), 3-91 (m, CH$_y$, 4H, J = 2 Hz), 3-60 (br, CH$_z$, 2H, 2-66 (s, CH$_w$, 4H, 2-54 (s, CH$_v$, 4H, 1-39 (s, C(CH$_h$)$_o$, 18H), 1-27 (s, C(CH$_h$)$_o$, 18H) ppm. $^{13}$C NMR (75 MHz, CDCl$_3$): δ 153-3, 140-4, 136-1, 124-9, 123-5, 121-5, 56-6, 55-8, 55-1, 48-6, 35-1, 34-2, 31-9, 29-8, 24-9, 24-6 ppm. EA found: C 76-10, H 10-20, N 5-15; calculated: C 76-28, H 10-31, N 4-94%.

3.2.3 Synthesis of [H$_2$O$_2$NN]$^m_0$ (1e)

Figure 2. Plots of ln([M]$_0$/[M]) versus time (♦) and $M_n$ versus percent conversion (•) for ring-opening polymerization of ε-caprolactone by 3a (2a and 2b) and 3b (2c and 2d) at 50°C in benzene-$d_6$ with [M]/ [Al] = 100. [Al] for 3a = 6.2 µM, [Al] for 3b = 4.2 µM. For plots of $M_n$ versus percent conversion, the solid line represents the theoretical molecular weight of poly(ε-caprolactone) calculated.

3.3 Synthesis and characterization of Al-alkyl complexes

\[ \text{CH}_x, 8\text{H}, 1.77 \text{ (br, CH}_x, 4\text{H, 1.56 \text{ (br, CH}_x, 2\text{H, 1.41 \text{ (s, C(CH}_h)_o, 18\text{H, 1.28 \text{ (s, C(CH}_h)_o, 18\text{H ppm.} \text{^{13}C NMR (75 MHz, CDCl}_3) \delta 153.3, 140.4, 136.1, 124.9, 123.5, 121.5, 56.6, 55.8, 55.1, 48.6, 35.1, 34.2, 31.9, 29.8, 24.9, 24.6 ppm. EA found: C 76.10, H 10.20, N 5.15; calculated: C 76.28, H 10.31, N 4.94%.} \]
3.3.2 Synthesis of AlMe[O,N]pr (2d)
Following the procedure outlined for 2c, [H₂O,N]pr (3.50 g, 6.18 mmol) and trimethylaluminum (2.41 g, 6.18 mmol) yielded 0.98 g (26%) of AlMe[O,N]pr as a white powder. 1H NMR (300 MHz, CDCl₃): δ 7.01, 7.00 (2H, J = 2 Hz), 6.41 (d, CH-phenoxide, 2H, J = 13 Hz) ppm. 13C NMR (75 MHz, CDCl₃): 138.1, 129.6, 123.1, 121.1, 59.4, 52.2 ppm. EA found: C 74.84, H 8.44, N 4.02%; calculated: C 75.11, H 8.29, N 4.02%.

3.3.3 Synthesis of AlMe[O,N]pr (2e)
Following the procedure outlined for 2c, [H₂O,N]pr (4.02 g, 7.10 mmol) and trimethylaluminum (2.71 g, 7.10 mmol) yielded 2.90 g (67%) of AlMe[O,N]pr as a white solid. 1H NMR (300 MHz, CDCl₃): δ 7.01 (2H, J = 3 Hz), 6.42 (d, CH-phenoxide, 2H, J = 13 Hz), 6.39 (d, CH₂, 2H, J = 7 Hz) ppm. 13C NMR (75 MHz, CDCl₃): δ 137.9, 128.9, 128.2, 127.5, 125.3, 124.6, 121.9, 59.3, 58.2 ppm. EA found: C 73.11, H 9.45, N 3.93%; calculated: C 73.23, H 9.45, N 3.93%.

3.4 Synthesis of characterization of Al-alkoxide complexes
3.4.1 Synthesis of AlOBn[O,N]mm (2a)
To a solution of AlOBn[O,N]mm (0.500 g, 0.886 mol) dissolved in 5 mL of toluene was added benzyl alcohol (0.116 g, 1.07 mmol). The mixture was allowed to stir for 3 h at ambient temperature. The toluene was then removed under reduced pressure and the remaining white residue was washed with 5 mL of pentane. The white solid was dried under reduced pressure yielding 0.140 g (27%) of AlOBn[O,N]mm. 1H NMR (300 MHz, CDCl₃): δ 7.78-7.74 (2H, J = 2 Hz), 7.59 (6-d, CH-phenoxide, 2H, J = 2.5 Hz), 7.35 (t, CH₃CH₂O, 2H, J = 7.4 Hz), 7.31 (t, CH₃CH₂O, 2H, J = 7.4 Hz) ppm. 13C NMR (75 MHz, CDCl₃): δ 155.6, 138.3, 138-1, 126.3, 127.3, 127.6, 123.6, 122.1, 61.4, 58.5, 54.3, 48.0, 34.9, 33.7, 31.5, 29.4 ppm. EA found: C 71.85, H 9.47, N 4.26%.

3.4.2 Synthesis of AlOBn[O,N]mm (2b)
Following the procedure for 3a, AlOBn[O,N]mm (1.50 g, 2.49 mmol) and benzyl alcohol (0.240 g, 2.22 mmol) yielded 1.41 g (98%) of AlOBn[O,N]mm as a white solid. 1H NMR (300 MHz, CDCl₃): δ 7.78-7.74 (2H, J = 2 Hz), 7.58 (6-d, CH-phenoxide, 2H, J = 2.7 Hz), 7.46 (m, CH₃CH₂O, 2H, J = 2.5 Hz), 6.78 (d, CH-phenoxide, 2H, J = 1.5 Hz) ppm. 13C NMR (75 MHz, CDCl₃): δ 155.6, 138.3, 138-1, 126.3, 127.3, 127.6, 123.6, 122.1, 61.4, 58.5, 54.3, 48.0, 34.9, 33.7, 31.5, 29.4 ppm. EA found: C 71.95, H 9.32, N 4.02%.

3.4.3 Synthesis of AlOBn[O,N]mm (2c)
Following the procedure for 3a, AlOBn[O,N]mm (0.500 g, 0.886 mmol) and benzyl alcohol (0.116 g, 1.07 mmol) yielded 0.32 g (56%) of AlOBn[O,N]mm as a white solid. 1H NMR (300 MHz, CDCl₃): δ 7.78 (2H, J = 2 Hz), 7.59 (d, CH-phenoxide, 2H, J = 1.5 Hz) ppm. 13C NMR (75 MHz, CDCl₃): δ 155.6, 138.3, 138-1, 126.3, 127.3, 127.6, 123.6, 122.1, 61.4, 58.5, 54.3, 48.0, 34.9, 33.7, 31.5, 29.4 ppm. EA found: C 71.95, H 9.32, N 4.02%.

3.4.4 Synthesis of AlOBn[O,N]mm (2d)
Following the procedure outlined for 3a, AlOBn[O,N]mm (0.500 g, 0.886 mmol) and benzyl alcohol (0.116 g, 1.07 mmol) yielded 0.32 g (56%) of AlOBn[O,N]mm as a white solid. 1H NMR (300 MHz, CDCl₃): δ 7.78-7.74 (2H, J = 2 Hz), 7.59 (d, CH-phenoxide, 2H, J = 1.5 Hz) ppm. 13C NMR (75 MHz, CDCl₃): δ 155.6, 138.3, 138-1, 126.3, 127.3, 127.6, 123.6, 122.1, 61.4, 58.5, 54.3, 48.0, 34.9, 33.7, 31.5, 29.4 ppm. EA found: C 71.95, H 9.32, N 4.02%.
3.5 General polymerization procedure for rac-lactide
A total of 0.020 g of Al-alkoxide catalyst (3a–e) and 100 molar equivalents of rac-lactide were added to an oven-dried ampoule charged with a magnetic stirrer bar. The ampoule was sealed and heated to 120°C with stirring for 6 h, after which the resulting viscous mixture was dissolved in a 10:1 dichloromethane/methanol solution. Once fully dissolved, the solution was left to stir at ambient temperature for 30 min, followed by precipitation into 100 mL of cold methanol. The resulting white precipitate was filtered and dried under vacuum to constant weight.

3.6 General polymerization procedure for ε-caprolactone
A total of 0.020 g of Al-alkoxide catalyst (3a–e) was dissolved in 5 mL of toluene and added to an oven-dried ampoule charged with a magnetic stirrer bar. To this solution, 100 molar equivalents of ε-caprolactone was added. The ampoule was sealed and heated to 50°C with stirring for 3 h, or at 25°C for 30 min. Once the desired polymerization time was reached, the polymerization was quenched with 1 mL of glacial acetic acid. The solution was left to stir at ambient temperature for 30 min which was followed by precipitation into 40 mL of cold pentane. The resulting white precipitate was filtered and dried under vacuum to constant weight.

4. Conclusion
Al-alkyl amine-bis(phenolate) complexes 2a–e were prepared in reasonable isolated yields by treatment of ligands 1a–e with trimethylaluminum. Single crystals of 2c showed a distorted tetrahedral aluminum complex where the pendant amine donor was uncoordinated in the solid state. The active aluminum-alkoxide initiating species was synthesized through addition of benzyl alcohol to 2a–e, allowing access to 3a–e in acceptable yields. The ability of novel complexes 3c–e to mediate ROP of rac-lactide was excellent, as there was excellent correlation between experimental and theoretical molecular weights accompanied by narrow molecular weight distributions. Living polymerization character was observed in kinetic studies of these polymerizations. 3c–e successfully controlled the ROP of ε-caprolactone when polymerization temperatures were lowered to 25°C. A drastic increase in control was observed for 3d and 3e, but this increase was not observed for 3c. 3a was only moderately active at this temperature, and 3b produced only trace amounts of PCL. A substantial loss of control was observed when the polymerization temperature was increased 50°C for 3c–e. Kinetic studies could not be completed for 3c–e due to high activity at room temperature, however 3a and 3b showed living character at 50°C. It has been concluded that while not crucial for ROP of rac-lactide, coordination of the pendant donor arm plays a significant role in controlling ROP of ε-caprolactone. It appears as though coordination of the pendant arm limits access of ε-caprolactone to the aluminum center, thus improving molecular weight distributions.

5. Supplementary information
X-ray crystallography data tables for complex 2c can be found in the supplementary information. In order to access this data file please refer to the supplementary data URL as mentioned at the end of the abstract.

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