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Magnesium Pyrazolyl-Indolyl Complexes as Catalysts for Ring-Opening Polymerization of L-Lactide

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Abstract: A series indole-based ligand precursors, $Pz^{R}IndH$ (R = H, $Pz^{H}IndH$; R = Me, $Pz^{Me}IndH$; R = t-Bu, $Pz^{tBu}IndH$; and R = Ph, $Pz^{Ph}IndH$), have been synthesized via copper-catalyzed *N*-arylation (for $Pz^{H}IndH$) or the Bartoli indole synthesis (for $Pz^{Me}IndH$, $Pz^{tBu}IndH$ and $Pz^{Ph}IndH$) reactions with moderate to high yield. Reactions of these ligand precursors with 0.7 equivalent of $Mg^{n}Bu_2$ in THF (for **1**) or hexane (for **2**–**4**) afforded the bis-indolyl magnesium complexes **1**–**4**, respectively. All the ligand precursors and related magnesium complexes have been characterized by NMR spectroscopy and elemental analyses. The molecular structure is reported for compound **1**. These novel magnesium complexes demonstrate efficient catalytic activities for the ring-opening polymerization of L-lactide in the presence of alcohol.

Keywords: magnesium; pyrazolyl; indolyl; ring-opening polymerization; biodegradable

1. Introduction

Polyesters, such as poly(ε-caprolactone) (PCL) or polylactide (PLA), are known as synthetic biodegradable polymers. These polymers have found applications in diverse fields, such as tissue engineering or bio-medical fields because of their biocompatible properties [1–5]. Due to the promising catalytic activities, metal-based initiators/catalysts have been attractive interest over the past decades [6–14]. Among these studies, some metal complexes bearing anionic *N*-heterocyclic ligands, such as pyrrole [15–26], indole [27,28] or carbazole [29], have displayed good catalytic activities towards ROP (ring-opening polymerization) of cyclic esters. The indole ring system, one of the most important heterocycles in nature, keeps continuous attraction due to the potential biological activities demonstrated by various indole derivatives. Therefore, development of novel routes for the preparation of indole derivatives has become an important theme in organic synthesis [30–34]. Recently, some magnesium complexes bearing pendant indolyl ligands have been reported by us [28]. They demonstrated efficient catalytic activities towards the ROP of cyclic esters. Considering the catalytic activities demonstrated by some pyrazolyl-containing magnesium complexes [35–38], we intended to introduce the pyrazolyl substituents as pendant functionalities into indole. We expected the combination of pyrazole and indole groups could be the candidates for ligand precursors. Therefore, we reported here the synthesis of magnesium complexes incorporating pyrazolyl-indolyl ligands. Their catalytic activities towards the ROP of L-lactide were also investigated.

2. Experimental Section

2.1. General Information

All manipulations were carried out under an atmosphere of dinitrogen using standard Schlenk-line or drybox techniques. Solvents were refluxed over the appropriate drying agent and distilled prior to use. Deuterated solvents were dried over molecular sieves.

^{1}H and ^{13}C{^{1}H} NMR spectra were recorded either on Varian Mercury-400 (400 MHz) or Varian Inova-600 (600 MHz) spectrometers (Agilent Technologies, Santa Clara, CA, USA) in chloroform-*d* or benzene-d_6 at room temperature unless stated otherwise and referenced internally to the residual solvent peak and reported as parts per million relative to tetramethylsilane. Elemental analyses were performed by an Elementar Vario ELIV instrument (Elementar, Hanau, Germany). The GPC measurements were performed in THF at 35 °C with a Waters 1515 isocratic HPLC pump, a Waters 2414 refractive index detector, and Waters styragel column (HR4E) (Waters, Milford, MA, USA). The number-average molecular weights (*M*n) and molecular weight distributions (PDIs = *M*w/*M*n) were calculated using polystyrene as standard.

N,*N*′-Dimethylethylenediamine (DMEDA, Acros, Geel, Belgium), pyrazole (Acros), K_2CO_3 (Union Chemical Works, Hsinchu, Taiwan), copper(I) iodide (Acros), 9-anthracenemethanol (9-AnOH, Acros), vinyl magnesium bromide (1.0 M in THF, Sigma-Aldrich, St. Louis, MO, USA) and di-*n*-butyl magnesium (1.0 M in heptane, Sigma-Aldrich) were used as supplied. Benzyl alcohol (TEDIA) was dried over CaH_2 and distilled before use. L-Lactide (Bio Invigor, Taipei, Taiwan) was recrystallized from dry toluene prior to use. 7-Bromoindole [39], 3,5-dimethyl-1-(2-nitrophenyl)-1*H*-pyrazole [40], 3,5-di-tert-butyl-1-(2-nitrophenyl)-1*H*-pyrazole [40] and 3,5-diphenyl-1-(2-nitrophenyl)-1*H*-pyrazole [40] were prepared by the modified literature's methods.

2.2. Preparations

Pz^{H}IndH: To a flask containing 7-bromoindole (0.52 g, 2.70 mmol), K_2CO_3 (0.37 g, 2.70 mmol), CuI (0.05 g, 0.27 mmol) and 1*H*-pyrazole (0.20 g, 3 mmol), 3 mL toluene and DMEDA (0.07 mL, 0.68 mmol) were added at room temperature under nitrogen. The reaction mixture was heated at 110 °C for 5 days. The reaction mixture was allowed to cool to room temperature. Then, the mixture was extracted with a mixed solution of 20 mL ethyl acetate and 50 mL de-ionized water. The organic layer was separated and dried over magnesium sulfate. The filtrate was pumped to dryness to afford yellow oil. Crude product was purified using column chromatography (ethyl acetate: *n*-hexane = 1:10) to afford yellow oil. Yield, 0.35 g, 70%. ^{1}H NMR ($CDCl_3$, 400 MHz): δ(ppm) 6.46 (t, *J* = 2.0 Hz, 1H, Ar–H), 6.57 (m, 1H, Ar–H), 7.09 (m, 1H, Ar–H), 7.24 (d, *J* = 7.6 Hz, 1H, Ar–H), 7.28 (t, *J* = 3.2 Hz, 1H, Ar–H), 7.55 (d, *J* = 8.0 Hz, 1H, Ar–H), 7.76 (d, *J* = 1.2 Hz, 1H, Ar–H), 8.06 (d, *J* = 2.4 Hz, 1H, Ar–H), 10.37 (br, 1H, NH). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ(ppm) 102.5, 106.8, 109.3, 118.9, 119.4, 125.3, 126.8, 140.4 (Ar–CH), 125.1, 127.4, 130.7 (*tert*-C). Anal. Calc. for $C_{11}H_9N_3$ (*M*w. 183.21): C, 72.11%; H, 4.95%; N, 22.94%. Found: C, 71.85%; H, 4.95%; N, 23.07%.

Pz^{Me}IndH: To a flask containing 3,5-dimethyl-1-(2-nitrophenyl)-1*H*-pyrazole (0.65 g, 3.0 mmol) and 15 mL THF, 9 mL vinyl magnesium bromide (1.0 M in THF, 9 mmol) was added at −45 °C. After 1 h of stirring, the reaction mixture was added 10 mL saturated NH_4Cl (aq). The reaction mixture was allowed to warm to room temperature. Then, the mixture was extracted with a mixed solution of 20 mL ethyl alcohol and 50 mL de-ionized water. The organic layer was separated and dried over magnesium sulfate. The filtrate was pumped to dryness to afford brown oil. Crude product was purified using column chromatography (ethyl acetate:*n*-hexane = 1:5) to afford pale-yellow powder. Yield, 0.22 g, 35%. ^{1}H NMR ($CDCl_3$, 400 MHz): δ(ppm) 2.27 (s, 3H, CH_3), 2.34 (s, 3H, CH_3), 6.01 (s, 1H, Pz–H), 6.50 (t, *J* = 2.0 Hz, 1H, Ar–H), 7.04–7.12 (overlap, 3H, Ar–H), 7.57 (d, *J* = 7.2 Hz, 1H, Ar–*H*), 9.70 (br, 1H, N*H*). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ(ppm) 12.6, 13.5 (CH_3), 102.4, 106.8, 115.5, 118.8,

119.6, 125.0 (Ar–CH), 124.3, 130.1, 130.3, 140.2, 149.1 (*tert*-C). Anal. Calc. for $C_{13}H_{13}N_3$ (*M*w. 211.26): C, 73.91%; H, 6.20%; N, 19.89%. Found: C, 73.54%; H, 5.92%; N, 19.88%.

Pz^{tBu}IndH: This was prepared in a similar method to that for Pz^{Me}IndH by using 3,5-di-tert-butyl-1-(2-nitrophenyl)-1H-pyrazole (0.90 g, 3.0 mmol). The brown oil was purified by column chromatography (ethyl acetate:*n*-hexane = 1:5) to afford pale-yellow solid. Yield, 0.33 g, 37%. ^{1}H NMR ($CDCl_3$, 400 MHz): δ(ppm) 1.10 (s, 9H, $C(CH_3)_3$), 1.33 (s, 9H, $C(CH_3)_3$), 6.08 (s, 1H, Pz–H), 6.41 (t, *J* = 2.0 Hz, 1H, Ar–H), 6.94 (t, *J* = 2.4 Hz, 1H, Ar–H), 7.07 (t, *J* = 7.2 Hz, 1H, Ar–H), 7.19 (d, *J* = 7.2 Hz, 1H, Ar–H), 7.60 (d, *J* = 8.0 Hz, 1H, Ar–H), 8.45 (br, 1H, NH). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ(ppm) 30.3, 30.6 ($C(CH_3)_3$), 31.9, 32.0 ($C(CH_3)_3$), 100.5, 102.6, 118.8, 121.3, 121.7, 124.9 (Ar-CH), 126.4, 129.7, 133.5, 154.0, 161.3 (*tert*-C). Anal. Calc. for $C_{19}H_{25}N_3$ (*M*w. 295.42): C, 77.25%; H, 8.53%; N, 14.22%. Found: C, 77.65%; H, 8.11%; N, 14.44%.

Pz^{Ph}IndH: This was prepared in a similar method to that for Pz^{Me}IndH by using 3,5-diphenyl-1-(2-nitrophenyl)-1*H*-pyrazole (1.02 g, 3.0 mmol). The pale-yellow powder was washed with 10 mL ethanol to afford white solid. Yield, 0.47 g, 47%. ^{1}H NMR ($CDCl_3$, 400 MHz): δ(ppm) 6.59 (t, *J* = 2.4 Hz, 1H, Ar–H), 6.69 (d, *J* = 7.2 Hz, 1H, Ar–H), 6.83(s, 1H, Ar–H), 6.86 (t, *J* = 8.0 Hz, 1H, Ar–H), 7.23 (t, *J* = 2.8 Hz, 1H, Ar–H), 7.25–7.35 (overlap, 5H, Ar–H), 7.41–7.44 (overlap, 2H, Ar–H), 7.54 (d, *J* = 8.0 Hz, 1H, Ar–H), 7.91–7.93 (overlap, 2H, Ar–H), 9.44 (br, 1H, NH). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ(ppm) 102.9, 105.2, 117.3, 119.0, 119.8, 125.2, 125.7, 128.2, 128.4, 128.6, 128.7, 130.5 (Ar–CH), 124.3, 130.1, 130.3, 132.8, 145.0, 152.0 (*tert*-C). Anal. Calc. for $C_{23}H_{17}N_3$ (*M*w. 335.40): C, 82.36%; H, 5.11%; N, 12.13%. Found: C, 82.65%; H, 5.19%; N, 12.13%.

[Pz^{H}Ind]$_2$Mg·2THF (**1**): To a flask containing Pz^{H}IndH (0.183 g, 1.0 mmol) in 15 mL THF, 0.7 mL di-*n*-butyl magnesium (1.0 M, 0.7 mmol) was added at 0 °C. The reaction mixture was allowed to warm up to room temperature. After 16 h of stirring, the reaction mixture was filtered and off-white solid was washed with 5 mL hexane. The residue was pumped to dryness to afford white solid. Yield, 0.27 g, 54%. ^{1}H NMR ($CDCl_3$, 600 MHz): δ(ppm) 1.67 (br, 8H, CH_2), 3.48 (br, 8H, OCH_2), 6.41 (s, 2H, Ar–H), 6.67 (d, *J* = 2.4 Hz, 2H, Ar–H), 7.01 (t, *J* = 7.8 Hz, 2H, Ar–H), 7.19 (d, *J* = 7.2 Hz, 2H, Ar–H), 7.53 (s, 2H, Ar–H), 7.60 (s, 2H, Ar–H), 7.68 (d, *J* = 7.8 Hz, 2H, Ar–H), 8.27 (d, *J* = 1.8 Hz, 2H, Ar–H). ^{13}C{^{1}H} NMR ($CDCl_3$, 150 MHz): δ(ppm) 25.2 (CH_2), 68.4 (OCH_2), 101.4, 106.8, 107.3, 116.2, 119.0, 125.3, 128.8, 141.8 (Ar–CH), 134.1, 134.6, 136.7 (*tert*-C). Anal. Calc. for $C_{30}H_{32}MgN_6O_2$ (*M*w. 532.92): C, 67.61%; H, 6.05%; N, 15.77%. Found: C, 66.70%; H, 5.49%; N, 15.60%.

[Pz^{Me}Ind]$_2$Mg (**2**): To a flask containing Pz^{Me}IndH (0.21 g, 1.0 mmol) in 15 mL hexane, 0.7 mL di-*n*-butyl magnesium (1.0 M, 0.7 mmol) was added at 0 °C. The reaction mixture was allowed to warm up to room temperature. After 16 h of stirring, the reaction mixture was filtered to afford white solid. Yield, 0.27 g, 61%. ^{1}H NMR (C_6D_6, 600 MHz): δ(ppm) 1.26 (s, 6H, CH_3), 1.88 (s, 6H, CH_3), 5.33 (s, 2H, Ar–H), 6.79 (d, *J* = 7.2 Hz, 2H, Ar–H), 7.03 (d, *J* = 2.4 Hz, 2H, Ar–H), 7.10 (t, *J* = 7.8 Hz, 2H, Ar–H), 7.58 (d, *J* = 2.4 Hz, 2H, Ar–H), 7.96 (d, *J* = 7.8 Hz, 2H, Ar–H). ^{13}C{^{1}H} NMR (C_6D_6, 150 MHz): δ(ppm) 11.2, 13.8 (CH_3), 103.9, 108.8, 112.9, 116.2, 120.6, 137.0 (Ar–CH), 124.4, 135.3, 138.4, 144.2, 151.7 (*tert*-C). Anal. Calc. for $C_{26}H_{24}N_6Mg$ (*M*w. 444.81): C, 70.20%; H, 5.44%; N, 18.89%. Found: C, 70.94%; H, 6.01%; N, 18.65%.

[Pz^{tBu}Ind]$_2$Mg (**3**): This was prepared in a similar method to that for **2** by using Pz^{tBu}IndH (0.29 g, 1.0 mmol) to afford white solid. Yield, 0.45 g, 73%. ^{1}H NMR (C_6D_6, 600 MHz): δ(ppm) 0.92 (br, 18H, $C(CH_3)_3$), 1.10 (s, 18H, $C(CH_3)_3$), 6.23 (br, 2H, Ar–H), 6.91 (br, 2H, Ar–H), 6.96–7.02 (overlap, 4H, Ar–H), 7.18 (br, 2H, Ar–H), 7.93 (d, *J* = 7.2 Hz, 2H, Ar–H). ^{13}C{^{1}H} NMR (C_6D_6, 150 MHz): δ (ppm) 29.7, 31.2 ($C(CH_3)_3$), 32.6, 33.4 ($C(CH_3)_3$), 103.8, 105.5, 115.6, 117.2, 121.7, 137.2 (Ar–CH), 125.8, 134.5, 140.2, 160.7, 167.9 (*tert*-C). Anal. Calc. for $C_{38}H_{48}N_6Mg$ (*M*w. 613.13): C, 74.44%; H, 7.89%; N, 13.71%. Found: C, 74.51%; H, 8.14%; N, 13.72%.

[Pz^{Ph}Ind]$_2$Mg (**4**): This was prepared in a similar method to that for **2** by using Pz^{Ph}IndH (0.33 g, 1.0 mmol) to afford white solid. Yield, 0.45 g, 65%. ^{1}H NMR ($CDCl_3$, 400 MHz): δ(ppm) 6.34 (d, *J* = 7.6 Hz, 2H, Ar–H), 6.55 (d, *J* = 2.4 Hz, 2H, Ar–H), 6.60–6.64 (m, 4H, Ar–H), 6.85–6.92 (overlap, 6H, Ar–H), 7.16 (d, *J* = 2.4 Hz, 2H, Ar–H), 7.28 (d, *J* = 8.0 Hz, 4H, Ar–H), 7.34–7.43 (overlap, 10H,

Ar–H), 7.57 (d, *J* = 8.0 Hz, 2H, Ar–H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 150 MHz): δ(ppm) 102.4, 106.8, 115.28, 115.35, 119.8, 128.5, 128.7, 129.1, 129.2, 129.3, 137.0 (Ar–CH), 123.4, 129.4, 130.0, 134.1, 137.3, 148.2, 155.0 (*tert*-C). Anal. Calc. for $C_{46}H_{32}N_6Mg$ (*M*w. 693.09): C, 79.71%; H, 4.65%; N, 12.13%. Found: C, 79.05%; H, 5.01%; N, 11.82%.

Procedure for Polymerization of L-*Lactide*: Typically, to a flask containing prescribed amount of L-lactide, 0.025 mmol alcohol and 0.025 mmol catalyst precursor was added 5.0 mL solvent. The reaction mixture was stirred at prescribed temperature for the prescribed time. After the reaction was quenched by the addition of 2.5 mL acetic acid solution (0.35 N), the resulting mixture was poured into 20 mL *n*-hexane to precipitate polymers. Crude products were recrystallized from THF/hexane and dried *in vacuo* up to a constant weight.

2.3. Crystal Structure Data

Crystals were grown from concentrated THF solution for **1**, and isolated by filtration. Suitable crystals were mounted onto Mounted CryoLoop (HAMPTON RESEARCH, Aliso Viejo, CA, USA; size: 0.5–0.7 mm) using perfluoropolyether oil (Sigma-Aldrich, FOMBLIN®Y) and cooled rapidly in a stream of cold nitrogen gas using an Oxford Cryosystems Cryostream unit. Diffraction data were collected at 100 K using an OxfordGemini S diffractometer (Oxford Diffraction Ltd., Abingdon, UK). Empirical absorption correction was based on spherical harmonics, implemented in the SCALE3 ABSPACK scaling algorithm from CrysAlis RED (Oxford Diffraction Ltd.). The space group determination was based on a check of the Laue symmetry and systematic absences and was confirmed using the structure solution. The structure was solved by direct methods using a SHELXTL package [41]. All non-H atoms were located from successive Fourier maps, and hydrogen atoms were refined using a riding model. Anisotropic thermal parameters were used for all non-H atoms, and fixed isotropic parameters were used for H atoms. Some details of the data collection and refinement are given in Table 1.

CCDC reference number 1410371 for **1** contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Table 1. Summary of crystal data for compound **1.**

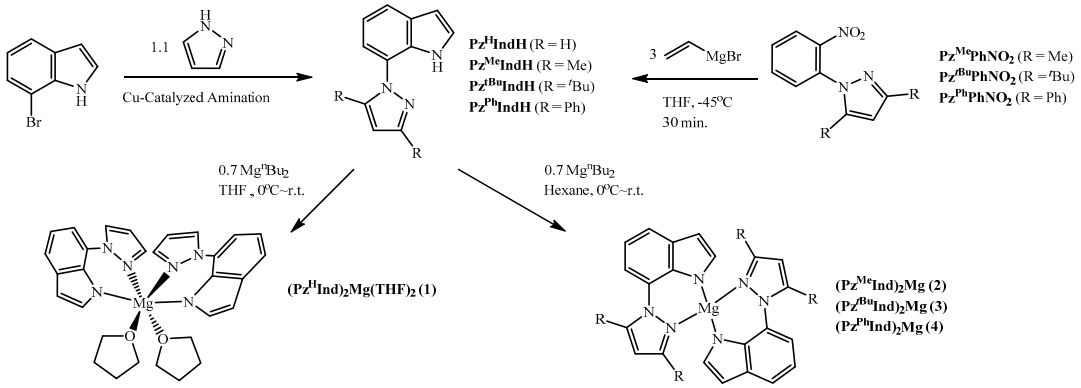
Parameters	1
Formula	$C_{30}H_{32}MgN_6O_2$
*F*w	532.93
T, K	100 (2)
Crystal system	Trigonal
Space group	*R*-3*c*
a, Å	23.6115 (3)
b, Å	23.6115 (3)
c, Å	26.0131 (5)
γ, °	120
V, Å^3	12,559.4 (3)
Z	18
ρ_{calc}, Mg/m^3	1.268
μ (Mo K_α), mm^{-1}	0.102
F(000)	5076
Crystal size	0.60 × 0.45 × 0.30 mm^3
Theta range for data collection	2.91° to 29.24°
Reflections collected	25,170
Independent reflections	3490 [R(int) = 0.0269]
No. of parameters	177
R1 [a]	0.0337
wR2 [a]	0.0893
GoF [b]	1.002

[a] $R1 = [\Sigma|F_0| - |F_c|]/\Sigma|F_0|$; $wR2 = [\Sigma w(F_0^2 - F_c^2)^2/\Sigma w(F_0^2)^2]^{1/2}$, $w = 0.10$; [b] GoF = $[\Sigma w(F_0^2 - F_c^2)^2/(N_{rflns} - N_{params})]^{1/2}$.

3. Results and Discussion

3.1. Preparations of Ligand Precursors and Magnesium Complexes

There are various synthetic routes for the preparation of indole derivatives, such as Fischer indole synthesis [32], Bartoli indole synthesis [31] or Pd/Cu-catalyzed cyclization [42,43]. Previously, we reported the preparation of indole bearing pendant functionalities using the Sonogashira reaction followed by Zn-mediated cyclization [28]. In order to introduce pyrazolyl functionalities into indole molecules, copper-catalyzed *N*-arylation or the Bartoli indole synthesis are used to achieve this issue. The synthetic routes were shown in Scheme 1.



Scheme 1. Synthetic routes for ligand precursors and magnesium complexes.

The ligand precursor Pz^{H}IndH was prepared via copper-catalyzed *N*-arylation reaction from 7-bromoindole with pyrazole [44]. Related ligand precursors composed of pyrazolyl rings bound to carbazole at the 1- and 8-positions have recently been reported [45]. The signal of –NH on ^{1}H NMR spectrum for indole Pz^{H}IndH was observed at δ 10.37 ppm. The ligand precursors Pz^{Me}IndH, Pz^{tBu}IndH and Pz^{Ph}IndH were prepared via the Bartoli indole synthesis from *o*-substituted nitrobenzenes with vinylmagnesium bromide [31]. The signals of –NH on ^{1}H NMR spectra for indoles Pz^{Me}IndH, Pz^{tBu}IndH and Pz^{Ph}IndH were observed at δ 9.70, 8.45, and 9.44 ppm, respectively. All the ligand precursors were characterized by elemental analyses as well.

Treatment of ligand precursors Pz^{R}IndH with $^{n}Bu_2Mg$ on the ratio of 1:0.7 by alkane elimination reaction in THF or hexane at room temperature affords the desired bis-indolyl magnesium complexes **1**–**4** in moderate yields, as shown in Scheme 1. For compound **1**, the disappearance of the N–H signal of indole and the appearance of the coordinated THF are consistent with the proposed structure. Preparations of compounds **2**–**4** bearing the coordinated THF have been done in THF. However, the signals corresponding to coordinated THF disappeared after rinsing the crude products with hexane. For the convenience of separation, THF was used to prepare compound **1**, whereas hexane was used to prepare compounds **2**–**4**. The compounds **1**–**4** were all characterized by NMR spectroscopy as well as elemental analyses.

Suitable crystals for structure determination of **1** were obtained from concentrated THF solution. The molecular structure is depicted in Figure 1. Selected bond lengths and bond angles are summarized in Table 2.

The solid state structure of **1** reveals that the Mg center adopts a distorted octahedral geometry ($N_{pyrazole}$–Mg–O_{THF} 175.46(3)°; $N_{indolyl}$–Mg–$N_{indolyl}$ 169.40(5)°) with the metal center chelated by two nitrogen atoms of indole rings, two nitrogen atoms of pyrazole rings and two oxygen atoms of coordinated THF. According to the coordinated THF positions of related magnesium complexes in the literature [46–48], the *cis*-configuration for **1** is observed (O_{THF}–Mg–O_{THF}, 87.62(4)°). The Mg–O_{THF} bond length of **1** (2.1516(8) Å) is longer than those found in *cis*-form (2.0661(10)–2.136(5) Å) [46–48].

The Mg–$N_{indolyl}$ bond lengths (2.1067(9) Å) are close to those found in magnesium bis-indolyl complexes (2.0907(16) Å for *trans*-form; 2.126(2) and 2.138(2) Å for *cis*-form) [28]. The Mg-$N_{pyrazole}$ bond lengths (2.2156(9) Å) are within those found in magnesium complexes bearing pyrazole functionality (2.100(3)–2.21(1) Å) [35–38].

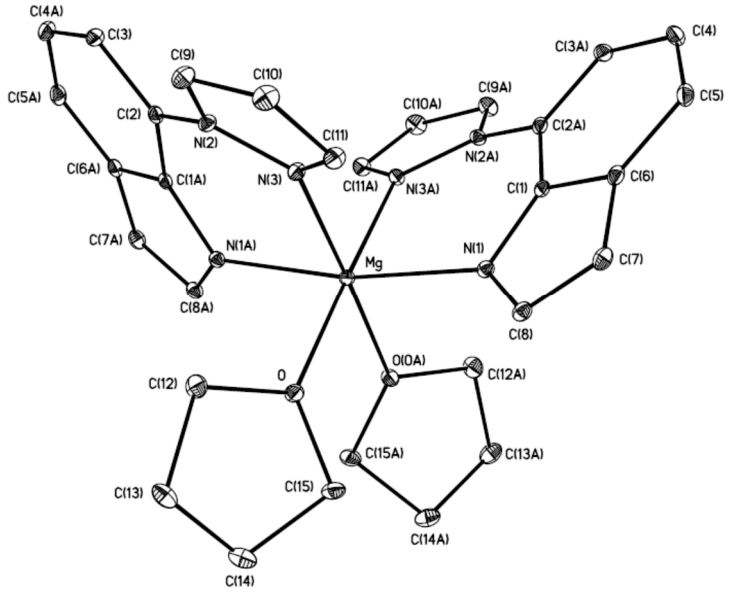


Figure 1. Molecular structure of **1**. Hydrogen atoms are omitted for clarity.

Table 2. Selected bond lengths (Å) and bond angles (°) for **1**.

Selected Bonds	(Å)	Selected Bond Angles	(°)
Mg–N(1)	2.1067 (9)	N(1)–Mg–N(1A)	169.40 (5)
Mg–N(3)	2.2156 (9)	N(1)–Mg–N(3A)	85.05 (3)
Mg–O	2.1516 (8)	O–Mg–O(0A)	87.62 (4)
		N(3)–Mg–O(0A)	175.46 (3)
		N(1)–Mg–O(0A)	91.36 (3)
		N(3)–Mg–N(3A)	96.38 (5)

3.2. Polymerization Studies

Since several magnesium complexes containing bis-indolyl ligands have demonstrated their catalytic activities towards the ROP of cyclic esters in the presence of alcohols [28], the homoleptic indolyl magnesium complexes reported here are expected to work as the catalysts for the ring opening polymerization. Representative results are collected in Table 3 for ROP of L-LA, respectively.

The polymerization of L-lactide using complexes **1–4** as catalyst precursors in the presence of alcohols is tested under a dry nitrogen atmosphere. Prescribed equivalent ratios on the catalyst precursor (0.025 mmol), L-LA and alcohol were introduced in 5.0 mL solvent at 0 °C for 1 min. After several trials on running polymerization with various solvents (dichloromethane, tetrahydrofuran or toluene) and alcohols (benzyl alcohol (BnOH), 2-propanol (^{i}PrOH) and 9-anthracenemethanol (9-AnOH)), the conditions were optimized to be toluene at 0 °C in the presence of 9-AnOH for the polymerization of L-LA (Table 1, Entries 1–5). However, only trace polymers were obtained from the blank tests in the absence of benzyl alcohol or **4** under the optimized conditions (Table 1, Entries 6–7). The same optimized conditions were applied to examine the catalytic activities of these catalysts with the reaction time extended to 5 min (Table 1, Entries 8–11). Only trace polymers obtained by using **1** as catalyst, this is consistent with the result demonstrated by magnesium bis-indolyl

complex with pendant amine functionality and coordinated THF molecules [28]. The bulkiness around the metal center caused by ligands and coordinated THF molecules might prevent the metal center from the coordination of monomers and alcohol. The catalytic activities exhibited by the other complexes without coordinated THF molecule seem to depend on the steric hindrance resulting from the substituents on the pyrazolyl groups. The decreasing tendency of catalytic activity was found in the order **3** > **4** > **2**. The catalytic activities were re-examined on the ratio of $[\text{L-LA}]_0/[\text{Mg}]_0/[\text{9-AnOH}]_0$ = 200/1/1 within 15 min. (Table 1, Entries 12–13). Complex **4** showed better activities than **3** with better controlled character. Therefore, complex **4** was subjected to exhibit the living character at 30 °C. The linear relationship between the number-average molecular weight (*M*n) and the monomer-to-initiator ratio (range from 150 to 400) was demonstrated in Figure 2 (Table 1, Entries 14–19, PDIs = 1.22–1.39) with poor controlled character.

Table 3. Polymerization of L-LA using compounds **1–4** as catalysts in toluene if not otherwise stated. [a]

Entry	Catalyst	$[\text{LA}]_0:[\text{Mg}]_0:[\text{ROH}]$	*T* (°C)	*t* (min)	*M*n (obsd) [b]	*M*n (calcd) [c]	Conversion (%) [d]	*M*w/*M*n [b]
1	**4**	100:1:1	0	1	14,000	10,300	70	1.20
2 [e]	**4**	100:1:1	0	1	–	–	61	–
3 [f]	**4**	100:1:1	0	1	–	–	6	–
4 [g]	**4**	100:1:1	0	1	–	–	20	–
5 [h]	**4**	100:1:1	0	1	–	–	15	–
6	**4**	100:1:0	0	1	–	–	trace	–
7	**4**	100:0:1	0	1	–	–	trace	–
8	**1**	100:1:1	0	5	–	–	trace	–
9	**2**	100:1:1	0	5	18,800	11,700	80	1.05
10	**3**	100:1:1	0	5	24,200	14,300	98	1.38
11	**4**	100:1:1	0	5	17,400	13,600	93	1.25
12	**3**	200:1:1	0	15	33,400	25,800	89	1.42
13	**4**	200:1:1	0	15	27,800	27,600	95	1.24
14	**4**	150:1:1	30	3	27,000	21,000	96	1.29
15	**4**	200:1:1	30	5	33,000	28,700	99	1.39
16	**4**	250:1:1	30	7	41,900	35,500	98	1.38
17	**4**	300:1:1	30	10	46,200	42,600	98	1.36
18	**4**	350:1:1	30	15	48,500	50,100	99	1.22
19	**4**	400:1:1	30	20	55,800	57,200	99	1.32
20	**4**	600:1:2	30	12	43,600	42,800	99	1.20
21	**4**	600:1:3	30	7	31,100	28,200	98	1.20
22	**4**	600:1:4	30	5	23,200	21,200	98	1.19

[a], $[\text{Mg}]_0$= [9-AnOH] = 0.025 mmol in 5.0 mL toluene; [b], Obtained from GPC analysis times 0.58; [c], Calculated from the molecular weight of lactide times $[\text{LA}]_0/[\text{ROH}]_0$ times conversion yield plus the molecular weight of ROH; [d], Obtained from ^{1}H NMR analysis; [e], In 5.0 mL CH_2Cl_2; [f], In 5.0 mL THF; [g], ROH = BnOH; [h], ROH = ^{i}PrOH.

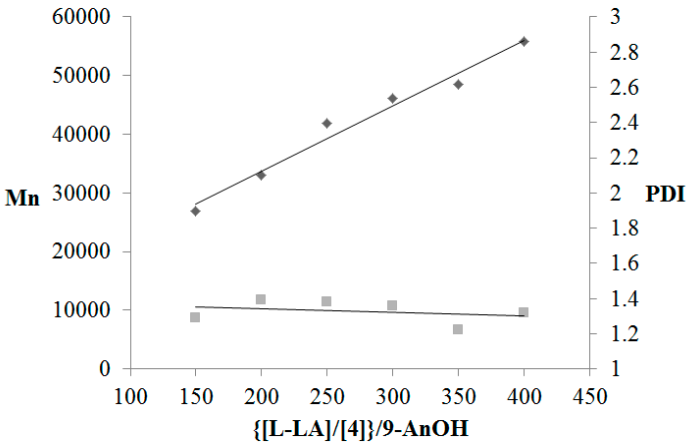


Figure 2. Polymerization of L-LA catalyzed by **4** in toluene at 30 °C (PDI = *M*w/*M*n in Table 3).

The "immortal" character was examined using 2–4 equivalents 9-AnOH as chain transfer agent to produce polymers with reasonable *M*n values (Table 1, Entries 20–22, compared to entries 17, 15, and 14, respectively). The end group analysis is demonstrated by the ^{1}H NMR spectrum of polylactide (PLA-100) catalyzed by **4** in the presence of 9-AnOH, which is shown in Figure 3.

Peaks are assignable to the corresponding protons in the proposed structure. The mechanism might be similar to that reported on magnesium complexes bearing pendant indolyl ligand, indicating the active magnesium alkoxide species might form first, followed by the coordination-insertion mechanism [28].

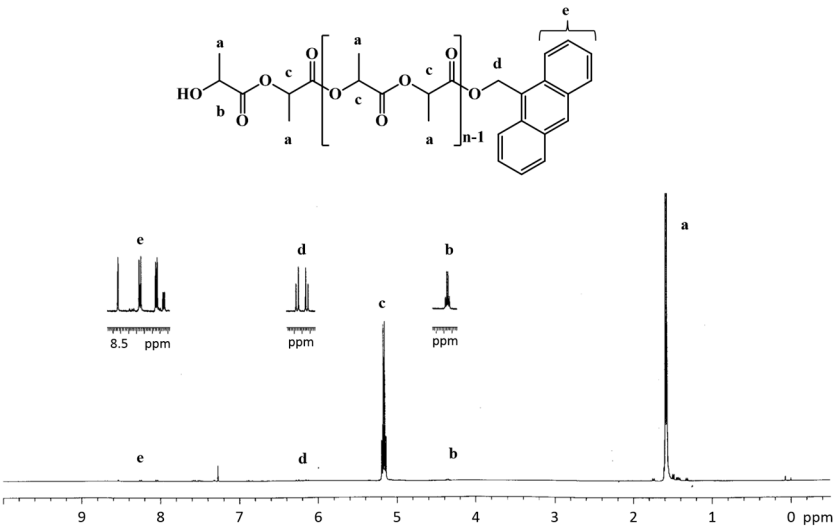


Figure 3. ^{1}H NMR spectrum of PLA-100 initiated by **4** in the presence of 9-AnOH in toluene at 0 °C.

4. Conclusions

Four indole ligand precursors containing pendant pyrazolyl functionalities have been prepared. The novel magnesium bis-indolyl complexes **1**–**4** have been synthesized and fully characterized by NMR spectroscopic studies and elemental analyses. Due to the steric hindrance of ligands, only complex **1** bearing two coordinated THF molecules in *cis*-configuration has been synthesized and confirmed by single-crystal X-ray crystallography. However, the crowded environment around the metal center of **1** might prevent the coordination of monomers or alcohols and result in poor catalytic activities. Under optimized condition, complex **4** demonstrated both living and immortal characters but with poor PDIs values (1.20–1.42). Preliminary studies on fine-tuning modification of indole ligands with different substituents and their application in the synthesis of metal complexes are currently underway.

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