# CHAPTER IV

# RESULTS AND DISCUSSION

In order to incorporate the flexible and –OH containing glycidol into PLLA, two copolymerization schemes were investigated. One is to add both monomers together at once in one polymerization step. The second is to first produce one block of homopolymer, which is then connected to another block of the other polymer.

In the first scheme, LLA and G were added into the reaction mixture together with various types of initiators, such as $Mg(OEt)_2$, (high reactivity initiator for copolymerization of cyclic anhydride and epoxide [19, 20]), $Al(O^iPr)_3$ (high reactivity initiator for copolymerization of cyclic anhydride and epoxide [20], and polymerization of LLA [27, 28]), and $SnPh_4$ or $Sn(Oct)_2$ (high reactivity initiators for polymerization of LLA [27]).

In the second scheme, block copolymer PG was first synthesized, followed by ROP of LLA using $Sn(Oct)_2$ and hydroxyl group of G as initiator and co-initiator, respectively. Structure of the copolymer thus depends on the structure of PG [33-36].

The outline of this thesis is as follows. In the beginning, the efficiencies of $Mg(OEt)_2$, $Al(O^iPr)_3$, $SnPh_4$, or $Sn(Oct)_2$ for the polymerization of either LLA or G were studied. Then, two polymerization schemes were investigated. In each section, detail characterization of polymer structure was carried out mainly by NMR spectroscopy. Molecular weight, physical appearance, and solubility of all products were also investigated.

### 4.1 Polymerization of LLA

$^1$H NMR of LLA (Fig. A-1) in $CDCl_3$, δ (ppm): 5.07 (-C<u>H</u>$CH_3$), and 1.71 (CHC<u>H</u>$_3$), and $^1$H NMR of PLLA (entry 6, Table 4.1, Fig. A-2) in $CDCl_3$, δ (ppm); 5.09 (-C<u>H</u>$CH_3$), and 1.51 (-CHC<u>H</u>$_3$).

From Table 4.1 entries 1-4, only LLA signals were observed from the NMR spectra. PLLA was not received both in anhydrous toluene and in bulk using $Mg(OEt)_2$ or $Al(O^iPr)_3$ as an initiator. The unsuccessful polymerization of LLA using $Al(O^iPr)_3$ as an initiator contradicts the work by Dubois *et al.* [28], which reported that $Al(O^iPr)_3$ was effective toward polymerization of LLA ($\overline{M}_w$ ca. 90,000) in anhydrous toluene at 70 °C. It is possible that the reaction time was too short to obtain high MW PLLA. Because in this work, the reaction time was limited to 2 days in order to compare the efficiency with other initiating systems. Only the bulk polymerization using $SnPh_4$ (entry 5) and $Sn(Oct)_2$ (entry 6) could produce high molecular weight PLLA with reasonably high yield.

**Table 4.1** $\overline{M}_n$ and yield of PLLA prepared under $N_2$ atmosphere and conditions.

| Entry | % Initiator | Solvent | Temperature (°C) | % Yield | GPC | |
|---|---|---|---|---|---|---|
| | | | | | $\overline{M}_n$ | PDI |
| 1 | $Mg(OEt)_2$ | Bulk | 30 | NR * | - | - |
| 2 | $Mg(OEt)_2$ | Toluene | 70 | NR * | - | - |
| 3 | $Al(O^iPr)_3$ | Bulk | 130 | NR * | - | - |
| 4 | $Al(O^iPr)_3$ | Toluene | 70 | NR * | - | - |
| 5 | $SnPh_4$ | Bulk | 130 | 63 | 41447 | 1.5 |
| 6 | $Sn(Oct)_2$ | Bulk | 130 | 80 | 35139 | 1.6 |

* NR = no reaction (only LLA monomer remained as shown by NMR analysis).

## 4.2 Polymerization of Glycidol

### 4.2.1 Using $Mg(OEt)_2$, $Al(O^iPr)_3$, $SnPh_4$, or $Sn(Oct)_2$ as an Initiator

Fig. A-3 shows NMR signals of G in $D_2O$: 3.78 ppm (HOC<u>H</u>H′), 3.66 (-O<u>H</u>), 3.52 (HOCH<u>H</u>′). 3.04 (m, C<u>H</u>), 2.70 (CHC<u>H</u>H′), and 2.60 (CHCH<u>H</u>′). When polymerized, the signals at 2.70 and 2.60 ppm for methine and methylene protons of the epoxide ring should disappear. From Table 4.2, the NMR spectra from products in all entries reveal signals for methine and methylene protons connected to ether linkage at 4.00-3.00 ppm (-C<u>H</u>$_2$C<u>H</u>(C<u>H</u>$_2$OH)O- and C<u>H</u>$_2$C<u>H</u>OHC<u>H</u>$_2$O-). Nevertheless a small amount of the monomer remained in the products from entries 1 to 3.

The highest molecular weight obtained in this section is only 1,600-1,800 when using Sn-initiator. This is quite low when comparing to reports by others [21], that used $BF_3{\cdot}OEt_2$ as an initiator. It seems that the four initiators, which are categorized as 'coordination initiators' are not quite suitable to generate high molecular weight polyglycidol.

**Table 4.2** $\overline{M}_n$ and physical appearance of PG using 0.3 mol% initiator (100 °C, 3 days).

| Entry | Initiator | $\overline{M}_n$ (GPC) | Physical appearance |
|---|---|---|---|
| 1 | $Mg(OEt)_2$ | 844 | brown liquid |
| 2 | $Al(O^iPr)_3$ | 688 | yellow liquid |
| 3 | $SnPh_4$ | 1796 | yellow liquid |
| 4 | $Sn(Oct)_2$ | 1570 | yellow liquid |

### 4.2.2 Using $BF_3{\cdot}OEt_2$ as an Initiator

An alternate method to ring-opening polymerization of glycidol is to use 'cationic polymerization' approach. From the literature [21] $BF_3{\cdot}OEt_2$ worked well

to produce polyglycidol with the $\overline{M}_n$ as high as 6,800. In this study, effect of the addition sequence of the reagent and the reaction temperature on polymerization were investigated, as listed in Table 4.3.

**Table 4.3** $\overline{M}_n$ of PG obtained from polymerization of G using 0.06 mol% $BF_3{\cdot}OEt_2$ as an initiator, 2 days.

| Entry | Addition Order* | Temperature (°C) | Molecular weight obtained by | | | |
|---|---|---|---|---|---|---|
| | | | GPC | | MS | |
| | | | $\overline{M}_n$ | PDI | $\overline{M}_n$ | PDI |
| 1 | G → $BF_3$ | -30 to –10 | 2849 | 3.7 | 867 | 1.03 |
| 2 | G → $BF_3$ | -11 to –5 | 2569 | 3.5 | 835 | 1.02 |
| 3 | 1/3G → $BF_3$ → 1/3G → 1/3G | -11 to –5 | 3465 | 4.8 | 1328 | 1.25 |
| 4 | $BF_3$ → G (cool G, slowly added) | -15 | 2276 | 4.1 | 889 | 1.02 |
| 5 | $BF_3$ → G (cool G, slowly added) | -25 | 1687 | 6.3 | 880 | 1.02 |
| 6 | $BF_3$ → G (not cool G, slowly added) | -15 | 3350 | 7.4 | 865 | 1.03 |

* a → b = b was added to a.

A typical $^1H$ NMR spectrum of PG entry 3 is shown in Fig. A-5. The signals at 4.00-3.00 ppm belong to (-C$\underline{H_2}$C$\underline{H}$(C$\underline{H_2}$OH)O- and –C$\underline{H_2}$C$\underline{H}$OHC$\underline{H_2}$O-). In order to characterize the structure of PG, DEPT and $^{13}C$ NMR was also used as shown in Fig. A-6 a and b, respectively. All signals correspond to the value reported previously [21-23] as follows: (i) linear 1,3-unit ($L_{13}$): $\underline{C}H_2OH$ at 60.6, $\underline{C}H_2$ at 68.9, and $\underline{C}H$ at 79.2; (ii) linear 1,4-unit ($L_{1,4}$): both $\underline{C}H$ at 72.0, $\underline{C}HOH$ at 68.7; (iii) terminal unit (T): $\underline{C}H_2OH$ at 62.5, $\underline{C}HOH$ at 70.3, and the $\underline{C}H_2$ at about 70.4; (iv) dendritic unit: $\underline{C}H$ at 78.1, one $\underline{C}H_2$ 70.8, and the other at about 70.4 overlapping with a $\underline{C}H_2$ of a terminal unit. Therefore it is believed that the structure of PG is somewhat branched that occurred by two pathways; active chain end and activated monomer mechanism, explained earlier in Chapter II.

The molecular weight of PG obtained was analyzed by MALDI-TOF-MS. The $\overline{M}_n$ of the products from entries 1, 3, 4, and 5 calculated from MS were 800-900 Da. PG in entry 2 has the highest molecular weight of about 1,300 Da. Variation of addition step may also results in minor structure variation and molecular weight of polyglycidol.

### 4.3 Polymerization of GBn (Protected Glycidol)

Proton NMR of GBn (Fig. A-7) in $CDCl_3$, δ (ppm), 7.33 (aryl), 4.64 (PhC<u>H</u>H′O), 4.59 (PhCH<u>H′</u>O), 3.76 (BnOC<u>H</u>H′), 3.43 (BnOCH<u>′</u>), and 3.21 (C<u>H</u>), 2.80 (CHC<u>H</u>H′), and 2.63 (CHCH<u>H′</u>).

Proton NMR of PGBn (entry 8, Table 4.4, Fig. A-8) in $CDCl_3$, δ (ppm), 7.49-7.08 (aryl), 4.63-4.43 (PhC<u>H</u>H′), and 4.08-3.32 (-(C<u>H</u>$_2$C<u>H</u>(C<u>H</u>$_2$OBn)O)$_n$-).

The condition for polymerization of GBn in entry 1 is the same as used by Walatch and co-workers [25], who prepared linear polyglycidol from ethoxyethyl glycidyl ether (protected glycidol) using KO$^t$Bu as an initiator in anhydrous THF at 65°C. It, however, did not work for preparing polymer from GBn. Only the monomer remained in the reaction as analyzed by proton NMR, suggesting that KO$^t$Bu was inactive for the polymerization of GBn in anhydrous THF at 65 °C.

After the unsuccessful attempt to polymerize GBn using an anionic initiator, the study was switched to investigate two cationic initiators; $BF_3{\cdot}OEt_2$ and $SnCl_4$, as reported in many literatures. The use of $BF_3{\cdot}OEt_2$ and $SnCl_4$ somewhat successfully polymerized GBn, as observed by $^1$H NMR. The signal for ether linkage of PGBn at 4.08-3.32 ppm was detected. Nevertheless, a large significant of GBn monomer remained in the reaction even after 7 days. Only the polymerization at room temperature (30 °C) for 5 or 7 days using $SnCl_4$ could produce PGBn with of $\overline{M}_n$ 1,427 and 1,627, polydispersity of 1.19 and 1.15, respectively.

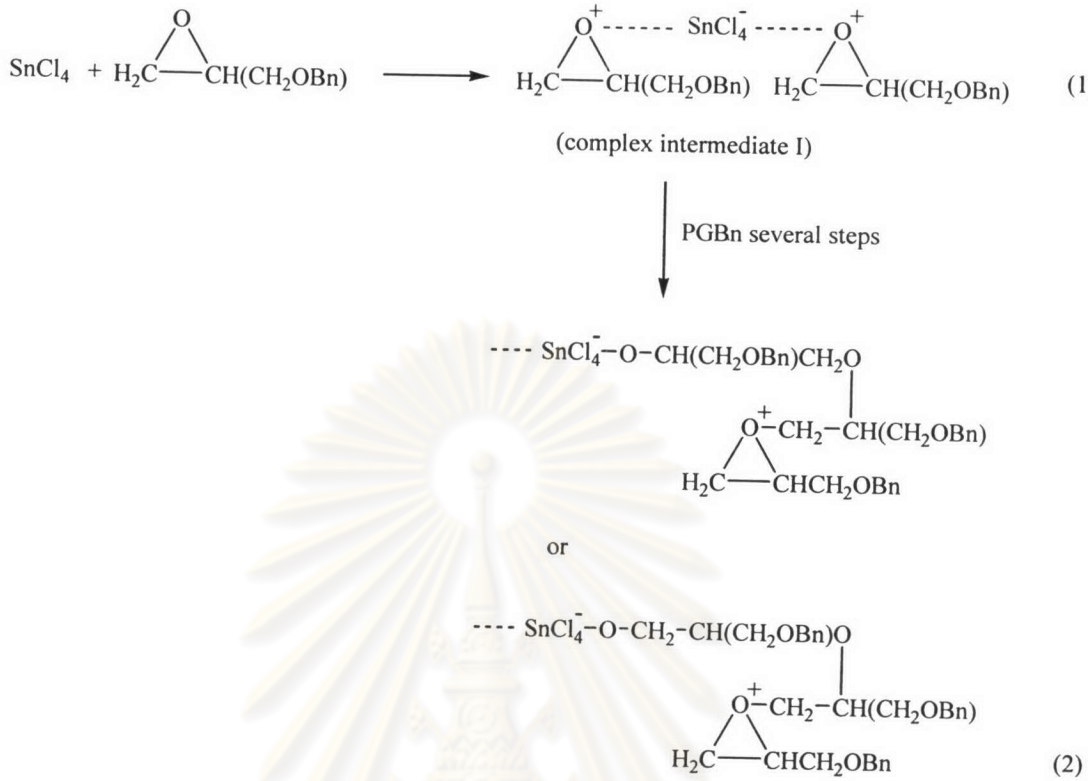
**Table 4.4** $\overline{M}_n$ and yield of PGBn obtained from polymerization of GBn using 0.8 mol% initiator.

| Entry | Initiator | Solvent | Temperature (°C) | Time (days) | % Yield | GPC | |
|---|---|---|---|---|---|---|---|
| | | | | | | $\overline{M}_n$ | PDI |
| 1 | KO$^t$Bu | THF | 65 | 2 | NR | NR | NR |
| 2 | $BF_3{\cdot}OEt_2$ | $CH_2Cl_2$ | -15 | 7 | NC | NC | NC |
| 3 | | Bulk | -15 | 7 | NC | NC | NC |
| 4 | | Bulk | 0 | 7 | NC | NC | NC |
| 5 | | Bulk | 30 | 7 | NC | NC | NC |
| 6 | $SnCl_4$ | Bulk | -15 | 7 | NC | NC | NC |
| 7 | | Bulk | -15 | 7 | NC | NC | NC |
| 8 | | Bulk | RT | 7 | 80 | 1,627 | 1.15 |
| 9 | | Bulk | RT | 5 | 82 | 1,427 | 1.19 |
| 10 | | Bulk | 50 | 7 | NC | NC | NC |

NR = No reaction- NMR spectrum shows only signals for GBn.

NC = Not complete- NMR spectrum shows signals of both PGBn and the monomer.

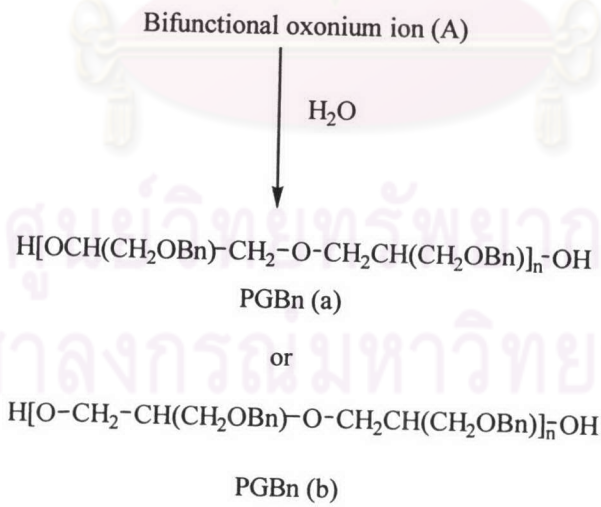
Francis *et al.* [37] suggested a mechanism for polymerization of epichlorohydrin using $SnCl_4$. The polymerization proceeded through cationic and co-ordination mechanism. According this suggestion, the polymerization of PGBn initiated by $SnCl_4$ also proceeded through cationic and co-ordination mechanism. In case of co-ordination mechanism, $SnCl_4$ forms a hexa-coordinate complex (complex intermediate I) with GBn as shown in Eq. 1, Scheme 4.1. The growing species in the polymerization is "bifunctional internal oxonium ion". The complex opens up by the reaction with GBn as shown in Eq. 2, Scheme 4.1. The "bifunctional oxonium ion" (A) terminates by reacting with water molecules resulting in the formation of PGBn (a) or (b), as shown in Eq. 3, Scheme 4.2.




(1)

(2)

**Scheme 4.1** Mechanism of $SnCl_4$ for polymerization of GBn.




(3)

**Scheme 4.2** Structure of PGBn.

From the above mechanism, the head-to-head (or tail-to-tail) and head-to-tail segments cause the irregular orientation of monomers along the polymer chain. Also

this leads to the formation terminal primary and secondary alcohol in the structures of PGBn.

## 4.4 Synthesis and Characterization of Model Compounds

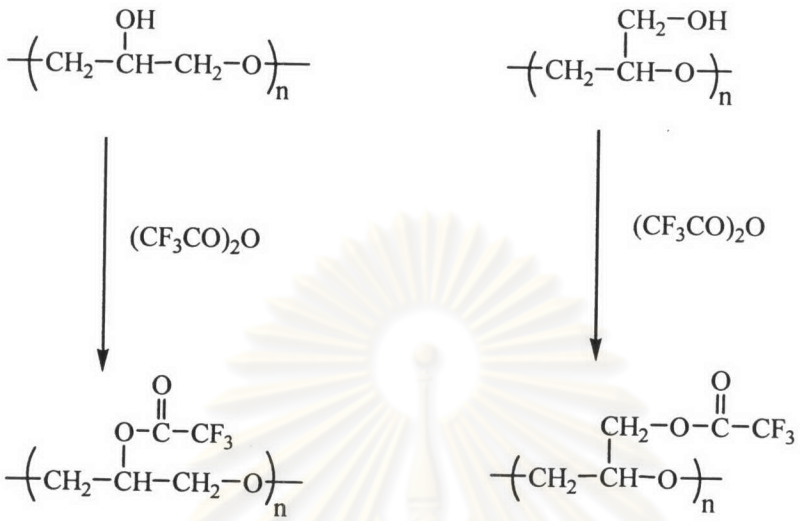
One of the requirements of this project is tc elucidate the structure of the LLA and G copolymers. The key point is to investigate how the ester linkage between the –OH of glycidol and the C=O of L-lactide can be identified in the NMR spectrum. Therefore, two model compounds: trifluoroacetate ester of polyglycidol and PLLA-co-glycerol were synthesized. Detail of the study is as follows.

### 4.4.1 Trifluoroacetate ester of Polyglycidol

Proton NMR of trifluoroacetate ester derivative of PG (PG-$OCOCF_3$) from PG entry 3, Table 4.3 (Fig. A-9) in $CDCl_3$, δ (ppm), 5.49-5.06 (-($CH_2C\underline{H}(OCOCF_3)CH_2O)_n$-), 4.73-4.00 (-($CH_2CH(C\underline{H_2}OCOCF_3)O)_n$-), and 4.00-3.00 (-($C\underline{H_2}C\underline{H}(CH_2OCOCF_3)O$)-$_n$ and (-($C\underline{H_2}CH(OCOCF_3)C\underline{H_2}O)_n$- of PG).

Trifluoroacetate-PG (Scheme 4.3) was used as a model to locate the chemical shift of methine and methylene on glycidol unit connected to the lactic acid via ester bonds. The $^1H$ NMR signal of trifluoroacetate-PG for the secondary alkyl ester (methine proton) is at 5.27 ppm and for the primary alkyl ester (methylene proton) is at 4.37 ppm (Fig. A-9). These two signals were confirmed by COSY spectra (Fig. A-10). Both signals coupled with CH and $CH_2$ of the PG unit (3.00 to 4.00 ppm). Moreover, careful inspection of the COSY spectra revealed that the proton of the secondary alkyl ester in fact coupled with the one of the primary alkyl ester. This could be that some terminal PG units contain two hydroxyl groups. The information from $^1H$ and COSY-NMR spectra of PG-acetyl ester derivative (Fig. A-9 and A-10) supported $^{13}C$ NMR spectra of PG (Fig. A-6) that the obtained PG contains primary and secondary alcohols which can be changed to primary and secondary ester.

This ester derivative was also used to determine the amount of hydroxyl chain end of the PG, by integrating the signals from proton NMR.




**Scheme 4.3** Synthesis of trifluoroacetate ester of PG.

### 4.4.2 PLLA and Glycerol Copolymer

The second model compound was a copolymer of LLA and glycerol (GL), an alcohol with three hydroxyl groups (Scheme 2.19). The synthesis followed Arvanitoyannis *et al.*, [34]. The molecular weight of PLLA-co-GL by GPC is 8,400 with polydispersity of 1.15.

The signals of interest are those belong to the primary and secondary alkyl esters on the glycerol unit. Proton and COSY NMR spectra (Fig. A-11 and A-12) of the model polymer indicate a proton signal of the secondary alkyl ester of GL (-C<u>H</u>O-PLLA) at 5.19 ppm, which overlaps with C<u>H</u>CH$_3$ of PLL. Another signal is at 4.42 ppm, which belongs to two protons of the primary alkyl ester of GL (-C<u>H$_2$</u>O-PLLA).

The $^1$H and COSY-NMR signals of primary and secondary PG acetyl ester derivative (Figure A-9 and A-10) corresponds with the $^1$H and COSY-NMR signals of primary and secondary ester of PLLA-co-GL. These evidences are used to confirm the position of $^1$H NMR signals of primary and secondary ester of branched PLLA-co-PG.

## 4.5 Synthesis of L-lactide and Glycidol Copolymers by Simultaneous Monomer Addition

In this section, attempts were made to synthesize copolymers of LLA and G by adding both monomers together into the polymerization vessel. Three LLA and G molar ratios were explored; 1:1, 5:1, and 9:1. Polymerization conditions and results of all three molar ratios are shown in Tables 4.5 to 4.7.

**Table 4.5** Polymerization conditions and results using LLA:G feed mole ratio = 1:1.

Initiator : 0.3 mol% of monomer
Temperature : 100 °C
Time : 1 day

| Entry | Initiator | Atmospheric control | % Yield[1] | $\overline{M}_n$ (GPC) | Physical Appearance |
|---|---|---|---|---|---|
| 1 | $Mg(OEt)_2$ | drying tube | 107 | 1,322 | viscous yellow liquid |
| 2 | | flow $N_2$ | 69 | *low*[2] | yellow liquid |
| 3 | | $N_2$ in balloon | 101 | 1,384 | viscous yellow liquid |
| 4 | | glove box[3] | 90 | *low*[2] | brown liquid |
| 5 | $Al(O^iPr)_3$ | drying tube | 89 | 1,184 | green liquid |
| 6 | | $N_2$ in balloon | 83 | *low*[2] | yellow liquid |
| 7 | | glove box[3] | 88 | *low*[2] | yellow liquid |
| 8 | $SnPh_4$ | drying tube | 80 | 1,190 | yellow liquid |
| 9 | | $N_2$ in balloon | 95 | *low*[2] | yellow liquid |
| 10 | | glove box[3] | 92 | *low*[2] | yellow liquid |
| 11 | $Sn(Oct)_2$ | glove box[3] | 87 | *low*[2] | yellow liquid |

[1] The yield is subjected to 10 % error because of the limitation in purification.

[2] The copolymer was not characterized by GPC. The molecular weight is presumable low because the product appearance was similar or less viscous when compared to the other products in the list.

[3] The reaction time was 3 days.

**Table 4.6** Polymerization conditions and results using LLA:G feed mole ratio = 5:1.

Initiator : 0.3 mol% of monomer
Temperature : 120 °C
Time : 7 days

| Entry | Initiator | Atmospheric control | % Yield | $\overline{M}_n$ (GPC) | Physical appearance |
|---|---|---|---|---|---|
| 1 | $Mg(OEt)_2$ | vac, balloon $N_2$ | 95 | 1,225 | white liquid |
| 2 | $SnPh_4$ | vac, balloon $N_2$ | 102 | 1,205 | yellow liquid |

**Table 4.7** Polymerization conditions and results using LLA:G feed mole ratio = 9:1.

Initiator : 0.3 mol% of monomer
Temperature : 120 °C
Time : 7 days

| Entry | Initiator | Atmospheric control | % Yield | $\overline{M}_n$ (GPC) | Physical appearance |
|---|---|---|---|---|---|
| 1 | $Mg(OEt)_2$ | drying tube | 42 | 1,521 | White liquid |
| 2 | $SnPh_4$ | drying tube | 79 | 945 | yellow liquid |

In case of copolymerization of 1:1 LLA:G feed molar ratio using $Mg(OEt)_2$, $Al(O^iPr)_3$, $SnPh_4$ or $Sn(Oct)_2$ as an initiator, proton NMR spectra in Fig. A-13 and A-14 show both G monomer and copolymer signal; 3.00-4.00 ppm (C<u>H</u> and C<u>H</u>$_2$ of PG), 4.2 ppm (C<u>H</u>$_2$OC(O)), and 4.4 ppm (C<u>H</u> chain end of PLLA). These four initiators are not active enough for the copolymerization of the two monomers, because the G monomer remained in the reaction.

Considering $Mg(OEt)_2$, even though the proportion of LLA was increased to 5 and 9 folds, the molecular weights of the products remained unchanged and were very low (~1,000 Da) (Tables 4.6 and 4.7). This observation indicates that $Mg(OEt)_2$ is really not reactive for activating the ring-opening of lactide. Only some glycidol can polymerize as indicated by small proton NMR signals at 3.00-4.00 ppm (Fig. A-15).

In the case of $SnPh_4$ for 5:1 LLA:PG feed molar ratio, proton NMR spectra (Fig. A-16) show signal of only the copolymer without G monomer left over. The copolymer was obtained in this case because $SnPh_4$ was highly reactive for the polymerization of LLA and moderately reactive for the polymerization of G. For the 9:1 case, LLA oligomer was the only product that could be identified, possibly because there were much higher content of LLA than G.

Because of the side reaction from –OH of G and low reactivity of the tested initiators [$Mg(OEt)_2$, $Al(O^iPr)_3$ $SnPh_4$ or $Sn(Oct)_2$], low molecular weight homo- and copolymers were obtained in all methods of atmospheric control (Table 4.5, Fig. A-13 and A-14). It appears that the effect of moisture on the copolymerization of LLA and G remains ambiguous.

From table 4.8, even though the LLA and G copolymer was obtained from the 1:1 LLA:G feed molar ratio using $Mg(OEt)_2$, $Al(O^iPr)_3$, $SnPh_4$, and $Sn(Oct)_2$ as an initiator and 5:1 LLA:G using $SnPh_4$ as an initiator, all $^1H$ NMR signals were too complicated to be assigned. This was due to the fact that solubility of the low molecular weight copolymer and the reactant (LLA and G) were very similar. Thus separating the oligomer products from the monomers was impossible. Consequently, to overcome this obstacle, the study was turned to produce block copolymers of LLA and G.

Table 4.8 exhibits identities of selected polymers analyzed by NMR.

**Table 4.8** Results from the polymerization of LLA and G using 0.3 mole% of various initiators (one step monomer addition).

| Initiator | LLA:G feed molar ratio | | |
|---|---|---|---|
| | 1:1 | 5:1 | 9:1 |
| $Mg(OEt)_2$ | Copolymer + G | LLA oligomer or low $\overline{M}_n$ copolymer | LLA oligomer or low $\overline{M}_n$ copolymer |
| $Al(O^iPr)_3$ | Copolymer + G | - | - |
| $SnPh_4$ | Copolymer + G | Copolymer | LLA oligomer |
| $Sn(Oct)_2$ | Copolymer + G | - | - |

### 4.6 Synthesis of Block Copolymer of LLA and G

Proton NMR spectrum of entry 1 in Table 4.9 (Fig. A-17a) in $CDCl_3$, δ (ppm); 5.36-5.05 (-C<u>H</u>$CH_3$ of PLLA and -C<u>H</u>O(COCH($CH_3$)O)$_n$-), 4.50-4.30 (-COC<u>H</u>($CH_3$)OH of PLLA), 4.30-4.10 (-C<u>$H_2$</u>O(COCH($CH_3$)O)$_n$-), 4.00-3.22 (-($CH_2$C<u>H</u>($CH_2$OH)O)$_n$- and (-($CH_2$C<u>H</u>OHC<u>$H_2$</u>O)$_n$-) of PG), 1.70-1.37 (-CHC<u>$H_3$</u> of PLLA) and COSY-NMR (Fig. A-21); 5.36-5.05 coupling with 1.70-1.37 (-C<u>H</u>$CH_3$ of PLLA coupling with -CHC<u>$H_3$</u> of PLLA), 5.36-5.05 coupling with 4.00-3.22 (-C<u>H</u>O(COCH($CH_3$)O)$_n$- coupling with -C<u>H</u> or -C<u>$H_2$</u> of PG unit), 4.30-4.10 coupling with 1.70-1.37 (-COC<u>H</u>($CH_3$)OH of PLLA coupling with -CHC<u>$H_3$</u> of PLLA), and 4.30-4.10 coupling with 4.00-3.22 (-C<u>$H_2$</u>O(COCH$CH_3$)$_n$- of PG coupling with -C<u>H</u> or -C<u>$H_2$</u> of PG unit).

**Table 4.9** Reaction conditions and results for block copolymerization of LLA and PG (130 °C, 1 day).

| Entry | LLA:PG (mol) | % $Sn(Oct)_2$[1] | Physical appearance | % Yield | GPC | |
|---|---|---|---|---|---|---|
| | | | | | $\overline{M}_n$ | PDI |
| 1 | 20:1 | 10 | viscous yellow liquid | 85 | 5,073 | 2.4 |
| 2 | 20:1 | 20 | viscous yellow liquid | 95 | 4,961 | 2.2 |
| 3 | 40:1 | 10 | yellow solid | 95 | 7,077 | 2.4 |
| 4 | 40:1 | 20 | yellow solid | 95 | 7,482 | 2.4 |
| 5 | 60:1 | 10 | white solid (soluble in MeOH) | 76 | 14,639 | 2.0 |
| | | | white solid (insoluble in MeOH) | 13 | 16,195 | 5.7 |
| 6 | 60:1 | 20 | white solid (soluble in MeOH) | 70 | 11,545 | 3.2 |
| | | | white solid (insoluble in MeOH) | 5 | 18,344 | 2.9 |

[1] Mol% of $SnOct_2$ was based on the total content of hydroxyl group in PG.

Proton and COSY NMR were used to identify the PLLA-*b*-PG copolymer (entry 1 from Table 4.9). The proton spectrum shows signals (Fig. A-17 a and A-21) that are the ester derivative of PG, *i.e.* primary and secondary alkyl ester signals from 5.30-5.06 and from 4.02-3.77 ppm, respectively. The COSY spectrum reveals that both signals coupled with proton at the ether segment of PG (3.77-3.28 ppm). From these two evidences, the ester linkage between the glycidol and lactide unit can be confirmed.

The molecular weights of PLLA-*b*-PG (entries 1-6, Table 4.9) increases as LLA:PG feed ratio increases. Increasing the % $Sn(Oct)_2$ from 10 to 20 % did not, however, raise the molecular weights of PLLA-*b*-PG (entry 1 *VS* 2, 3 *VS* 4, and 5 *VS* 6).

At high LLA feed ratio (60:1) in entries 5 and 6, two types of white solids having different solubilities in MeOH were obtained. From the molecular weight data, it is possible that the MeOH-insoluble portion is PLLA-co-PG having a longer PLLA segment than the MeOH-soluble copolymer. Proton and COSY-NMR of the main and by-product of PLLA-co-PG are exhibited in Fig. A-19, A-20, and A-25 to A-28. The other by-product was LLA oligomer which was separated after the purification step as viscous liquid.

Since the structure of polyglycidol is branching, it is expected that the structure of this PLLA-*b*-PG copolymer may be in the form 'core-shell' structure. Nevertheless, no prove has been made by the time of completing this thesis.

Solubility of PLLA-*b*-PG copolymers

The solubility of the copolymer was compared with the monomer and homopolymers in three solvents; $CH_2Cl_2$, MeOH, $H_2O$ (Table 4.10). It was found that PLLA-*b*-PG copolymers obtained can be dissolved in both $CH_2Cl_2$ and MeOH. It is interesting that the solubility of this block copolymer is the combination of each block which is PLLA (sol. in $CH_2Cl_2$/ insol. in MeOH) and PG blocks (sol. in MeOH/ insol. in $CH_2Cl_2$).

**Table 4.10** Comparison between solubility of branched PLLA-co-PG (from table 4.9) and the reactants (LLA, PLLA, and PG).

| Monomer or polymer | Soluble in | | |
|---|---|---|---|
| | $CH_2Cl_2$ | Methanol | $H_2O$ |
| LLA | + | + | + |
| PLLA | + | - | - |
| PG | - | + | + |
| PLLA-co-PG | + | + | - |

+ Soluble

- Insoluble

### 4.7 Copolymerization of L-lactide and Poly(benzyl glycidyl ether)

A proton NMR spectrum of the PLL-co-PGBn in Table 4.11 (Fig. A-29) reveals several signals as follows- 7.34-7.09 (aryl), 5.21-4.99 (C<u>H</u>O-PLLA and C<u>H</u>$CH_3$ of PLLA), 4.53-4.35 (C<u>$H_2$</u>-Ph), 3.89-3.62 (C<u>$H_2$</u>O-PLLA), 3.62-3.26 (C<u>$H_2$</u>C<u>H</u>(C<u>$H_2$</u>OBn)O), and 1.60-1.29 (CHC<u>$H_3$</u> of PLLA).

To confirm the copolymer structure, trifluoroacetate group was used to cap two hydroxyl end units of PGBn. The PGBn-$OCOCF_3$ was then analyzed by proton and COSY-NMR (Fig. A-31 and A-32). The spectra shows signals of secondary (-C<u>H</u>O$COCF_3$) and primary alkyl ester (-C<u>$H_2$</u>O$COCF_3$) at 5.31–5.14 and 3.92-3.68 ppm, respectively. These two signals also couple with the ether segment (C-O-C) of PGBn unit located at 3.68 to 3.11 ppm. These, therefore, indicates that PGBn contains both primary and secondary hydroxyl end groups.

From NMR spectra of PLLA-co-PGBn in Fig. A-29 and A-30, the signals of secondary alkyl ester [-C<u>H</u>OC(O)C$H(CH_3)$O-] from 5.21 to 4.99 ppm and primary alkyl ester [-C<u>$H_2$</u>OC(O)C$H(CH_3)$O-] from 3.89 ppm to 3.62 ppm corresponds with the primary and secondary ester signals of PGBn acetyl ester derivative (Fig. A-31 and

A-32). From these evidences, linear PLLA-co-PGBn was successfully synthesized with $\overline{M}_n$ = 1,768 and PDI = 1.58 (Table 4.11).

After deprotection of the benzyl group, $^1$H and COSY NMR spectra (Fig. A-33 and A-34) of linear PLLA-*b*-PG copolymer (86.3 % yield, $\overline{M}_n$ = 1,184, PDI = 1.85) was obtained. It is confirmed by the disappearance of the benzyl signal at 7.34-7.09 (aryl) and 4.53-4.35 ppm (-C$\underline{H_2}$Ph). The $^1$H NMR of the linear copolymer (in $CDCl_3$) shows peaks as follows: 5.32-5.09 (-C$\underline{H}$O-PLLA and -C$\underline{H}$CH$_3$ of PLLA), 4.00-3.83 (-C$\underline{H_2}$O-PLLA), 3.83-3.43 ((-C$\underline{H_2}$C$\underline{H}$(C$\underline{H_2}$OH)O-)$_n$), and 1.69-1.42 (-CHC$\underline{H_3}$ of PLLA) (Fig. A-33). The COSY spectrum of linear PLLA-*b*-PG copolymer (Fig. A-34) also indicates that the proton of the alkyl ester couples with the proton signals in the ether segment from 3.83-3.43 ppm. This signal coupling is the same as that found from the characterization of PLLA-co-PGBn (Fig. A-30).

**Table 4.11** Copolymerization condition and molecular weight (by GPC) of LLA and PGBn.

| LLA:PGBn (g/g) | $Sn(Oct)_2$ (mol%) | $\overline{M}_n$ of PGBn | PLLA-*b*-PGBn | | PLLA-*b*-PG | |
|---|---|---|---|---|---|---|
| | | | $\overline{M}_n$ | PDI | $\overline{M}_n$ | PDI |
| 1:1 | 10 | 1,427 | 1,678 | 1.58 | 1,184 | 1.85 |

[1] Mol% of total hydroxyl groups of PGBn.