Chapter 5: Synthesis and Characterization of Amine-Terminated Poly (methyl methacrylate) s via Group Transfer Polymerization

5.1 Introduction

Controlled synthesis of polymers with reactive functionality at the terminal end continues to be a synthetic challenge in polymer chemistry. End functional polymers are useful in a variety of applications, such as, compatibilizing agent for polymers via reactive processing, macromolecular surfactants, modification of surfaces etc. Several techniques of controlled polymerizations, namely, living anionic polymerization (LAP)\(^1\), group transfer polymerization (GTP)\(^2\) and controlled radical polymerization (CRP) such as atom-transfer polymerization (ATRP)\(^3\), stable free radical polymerization (SFRP)\(^3\), and reversible addition fragmentation transfer (RAFT)\(^3\) can be used for the synthesis of end-functionalized polymers. However, the nature of the polymer and the functional group to be introduced will determine the specific choice of synthetic methods.

End functionalized poly (methyl methacrylate) s can be synthesized either by living anionic polymerization or controlled radical or group transfer polymerization. In general, two approaches are possible via, use of functional initiators or termination of the “living” chain by a suitable electrophile (or radical precursors) bearing the functional groups. Either of the methods have both merits and demerits. For example, functional initiators having active hydrogen groups (-OH, -NH\(_2\)) cannot be directly used in LAP and will require a protection-deprotection sequence.

Use of electrophiles as terminating agents is not always efficient since in most cases, the active chain ends are in equilibrium with an inactive dormant species, which is incapable of reacting with the electrophile. An additional complication arises due to competing termination reactions, leading to loss of active chain ends.
In spite of these limitations, several attempts are reported in the literature for the synthesis of end-functionalized polymers by LAP\textsuperscript{4}, ATRP\textsuperscript{3a,5} and GTP\textsuperscript{6}. To obtain high efficiencies of functionalization, each method has to be carefully optimized in terms of the choice of the initiator and the polymerization conditions.

There are only few reports of amine end functional poly (methyl methacrylate) s (PMMA’s) in the literature. Amine end-functional polymers are of interest in several applications\textsuperscript{7a-c}. They can be used as an initiator for the synthesis of polypeptide block copolymers\textsuperscript{7a-d}.

Preparation of amine-terminated polymers by LAP invariably involve a post polymerization procedure to convert the end group into an amine group\textsuperscript{8}. 1-[4-[N, N-bis (trimethylsilyl) amino] phenyl]-1-phenylethylene and 1-(dimethylaminophenyl)-1-phenylethylene were used to prepare amine-terminated polymers\textsuperscript{8f-g} by living anionic polymerization. Nakahama et al reported high yields (96-100\%) of primary amine functionalized polystyrene by reacting polystyryllithium with 1.5-2 equivalents of the protected amine, namely, N-(benzyldene)-trimethylsilyl amine in benzene at 25°C \textsuperscript{8b}. In similar fashion primary amine terminated polystyrene have been prepared by the reaction of polystyryllithium with the product of reaction of methoxyamine and methyllithium at low temperature\textsuperscript{8}.

More recently, Mays and coworkers reported\textsuperscript{9} the synthesis of amine-terminated PMMA (Scheme 5.1) with $M_n = 3.5 \times 10^5$ g/mol and $M_w/M_n = 1.08$ by reacting the living anionic chain end with an electrophile, namely, 1-(3-bromopropyl)-N, N-(trimethylsilyl) amine in THF at -78°C, in high yields. MALDI-ToF-MS of the amine-terminated PMMA and polystyrene confirmed efficient chain termination reaction.

\begin{center}
\textbf{Scheme 5.1. Amine-terminated PMMA via LAP}
\end{center}
Amine-terminated PMMA with $M_{n, \text{SEC}} = 7750$-$66000$ g/mol were prepared by atom-transfer radical polymerization (ATRP) using CuBr/N, N', N'', N'''-pentamethyldiethylenetriamine (PMDETA) and with protected amine functional group bearing initiator$^{10a}$. However, under these conditions polymerization proceeds in an uncontrolled fashion. PMMA's with $M_n/M_n = 1.53$-$2.86$, initiator efficiency in the range of 1.06 to 0.17 and conversions in the range of 22-$98\%$ were obtained. In another approach, halogen end functional poly (acrylate) s prepared by ATRP was converted to the corresponding azide by nucleophilic displacement using NaN$_3$/DMF. The azide terminated acrylate polymer was further converted to phosphoranimines, which upon hydrolysis gave amine-terminated poly (acrylate) s$^{10b}$.

Dimethylamino-functionalized PMMA with $M_{n, \text{SEC}} = 2200$-$2500$, $M_n/M_n = 1.06$-$1.07$ and $F_n$ in the range of 0.93-$0.90$ was prepared using GTP$^{11}$ by the reaction of the living trimethylsilyl ketene acetal-ended PMMA with methyl $E$-3-(2-dimethylaminophenyl)-2-phenylacrylate (AMPA) using tris (dimethyl amino) sulfonium bifluoride (TASHF$_2$) at room temperature.

As a part of our studies aimed at exploring the scope of electrophilic termination approach of GTP chain ends for the synthesis of end functional PMMA’s, we herein report the preparation of amine terminated PMMA via GTP by the reaction of the silyl ketene acetal chain end of PMMA with N-trimethylsilyl benzaldimine. Silyl ketene acetals are reported to undergo facile reaction with aldimines to generate the desired amino functionality in good yields$^{12}$. The efficiency of polymer functionalization was examined using $^1$H NMR, SEC and MALDI-TOF methods.

### 5.2 Experimental Methods

#### 5.2.1 Materials

Diethyl ether (S.D. Fine Chemicals, Mumbai) was distilled over Na-benzophenone. ZnI$_2$ (99%, Aldrich, USA, 100-mesh) and tetra-n-butyl ammonium bibenzoate TBAF (1.0 M in THF, Aldrich, USA) were used as received. N-trimethylsilyl benzaldimine prepared according to reported procedure$^{12a}$. Tetra-n-butyl ammonium bibenzoate (TBABB) prepared according to procedure reported elsewhere$^{13}$. MeOH and t-BuOH (S.D. Fine Chemicals, Mumbai) dried and degassed before use.
Preparation of N-trimethylsilyl benzaldimine (3)
A flame dried 50 mL round bottom flask was charged with lithium hexamethyldisilazide (14.5 g, 0.0866 mols) inside a glove box. The flask was cooled to 0°C and dry THF (80 mL) was added. To this was added benzaldehyde (8.8 mL, 0.0866 mols) drop-wise. The resulting solution was stirred for 30 minutes at 0°C. Thereafter, trimethylsilylchloride (11 mL, 0.0866 mols) was added in one portion and stirring continued for 30 minutes at 0°C. The reaction mixture was warmed to room temperature and subjected to fractional distillation (55-60°C/0.05 mm Hg) yielding 13.8 g (90%) N-trimethylsilyl benzaldimine as pale green oil. The product was highly sensitive to oxygen and moisture and was therefore stored under nitrogen at 10°C.

$^1$H NMR (CDCl$_3$/200 MHz): $\delta$ 0.25 (s, 9H, SiMe$_3$), 7.4 (m, 3H, ArH), 7.7 (m, 2H, ArH), 8.93 (s, 1H, CH=N)

5.2.2 Model reaction between MTS (2) and N-trimethylsilyl benzaaldimine (3) using ZnI$_2$ in THF.
A flame dried 50 mL round bottom flask was charged with dry ZnI$_2$ (0.35 g, 1.15x10$^{-3}$ mol) inside a glove box. THF (20 mL) was added to the flask. N-trimethylsilyl benzaldimine (0.2 g, 1.15x10$^{-3}$ mol) was added and stirred for 5 minutes. MTS (0.3 mL, 1.15x10$^{-3}$ mol) and Bu'OCl (0.1 mL, 1.15x10$^{-3}$ mol) were added under nitrogen atmosphere in rapid succession and stirred at room temperature for 3 h. The crude product was washed with water and dried over Na$_2$SO$_4$. Purification using column chromatography yielded the amino-ester as a light yellow liquid in $\geq$ 93% isolated yield.

5.2.3 Synthesis of amine-terminated PMMA by GTP
A clean and flame dried two neck 250 mL reactor, equipped with a nitrogen inlet by means of three way septum adapter, a dropping funnel and a magnetic stir bar was charged with 1.2 mg of TBABB catalyst (2.35x10$^{-6}$ mol, 0.1mol% of MTS) in THF (1 mL), followed by dry THF (30 mL) was transferred using a canula under positive pressure of dry nitrogen. MTS (0.5 mL, 2.35x10$^{-3}$ mol) was added using syringe at room temperature. After 5 minutes, 5.0 mL of MMA (0.047 mol) was added using dropping funnel at approx. 1mL/min. The polymer solution was then added to 0.42 g of N-trimethylsilyl benzaldimine (2.35x10$^{-3}$ mol) activated by 2.35x10$^{-3}$ mol of ZnI$_2$ (0.7508 g) in THF followed by immediate addition of 0.23 g of t-BuOH (2.35x10$^{-3}$ mol).
mol). The reaction was allowed to continue for 12 h at room temperature. Later, subsequently, 2.35x10^{-3} \text{ mol} \text{ of } \text{NBu}_4\text{F/methanol} \text{ was added to the reaction mixture and reaction was continued for overnight at 25°C and the resulting reaction mixture was precipitated in hexane. The polymer solution was passed through neutral alumina and precipitated in hexane to obtain pure colorless polymer free of ZnI}_2. The polymer was further purified by reprecipitating it from THF solution using excess hexane. The obtained polymer was dried at 60°C in vacuum. Yield: 5.2 g (100%).

5.2.4 Characterization
The methods of characterization are described in chapter 2.

5.3 Results and Discussion
5.3.1 Model reaction between MTS and N-trimethylsilyl benzaldimine
To arrive at the most suitable conditions, initially model reactions were carried out between MTS (2) and N-trimethylsilyl benzaldimine (3) using 1.0 equivalent of ZnI}_2 based on MTS. Immediate addition of t-BuOH was necessary to avoid the formation of imino-ester (5) (Scheme 5.2).

Scheme 5.2. Reaction between MTS and N-trimethylsilyl benzaldimine
In the absence of t-BuOH, imino-ester is reported to form as the sole product due to competitive trans-amination between unreacted imine and a metallo-amide intermediate\textsuperscript{12a}. The results are shown in table 5.1. The reaction is equally efficient in THF and diethyl ether as solvents.

**Table 5.1. Reaction between MTS and N-TMS benzaldimine at 25ºC**

<table>
<thead>
<tr>
<th>Entry</th>
<th>N-TMS benzaldimine, mmol</th>
<th>ZnI(_2), mmol</th>
<th>t-BuOH, mmol</th>
<th>MTS, mmol</th>
<th>Solvent, mL</th>
<th>Time, h</th>
<th>Isolated Yield (β-amino ester) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>Diethyl ether, 10</td>
<td>3</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>THF, 10</td>
<td>3</td>
<td>93</td>
</tr>
</tbody>
</table>

Fig 5.1 shows the \(^1\)H NMR spectrum of β-amino ester (7), which showed a broad peak at δ 1.95 corresponding to two protons of the amino group.

Fig 5.2 shows the \(^13\)C NMR spectrum of β-amino ester (7) exhibiting peaks at δ 19.29 (2CH\(_3\)) at δ 51.67 (-OCH\(_3\)), at δ 61.71 (CH), at δ 127.65 (Ar-C), and at δ 177.57 (>C=O). The diastereotopic methyl groups could not be distinguished. FT-IR of β-aminoester (7) shows peaks at 1728 cm\(^{-1}\) for the ester group and at 3388 cm\(^{-1}\) for NH group.
5.3.2 Amine-terminated poly (methyl methacrylate) s via GTP

The GTP of MMA was carried out using MTS (2) as initiator in THF at 30°C using a nucleophilic oxyanion catalyst, TBABB (0.1 mol% based on MTS). Living trimethylsilyl ketene acetal-ended PMMA (8) was terminated using N-trimethylsilyl benzaldimine (3) and 1 equivalent of ZnI₂ as Lewis acid catalyst in THF resulting in the amine-terminated PMMA (10) (Scheme 5.3).

Scheme 5.3. Amine-terminated PMMA’s via GTP
Narrow molecular weight amine-terminated PMMA’s oligomers were prepared with initiator efficiencies in the range of 0.84-1.06. The number average degree of functionality ($F_n$) was found to be between 0.80-0.85 (table 5.2). A typical $^1$H NMR of amine-terminated PMMA in acetone-$d_6$ is shown in figure 5.3 (entry 1, table 5.2). $M_n$ was calculated from the NMR spectra by comparing the ratio of aromatic protons (at $\delta$ 7.4 ppm) with that of $-OCH_3$ protons (at $\delta$ 3.6 ppm) of PMMA.

Figure 5.3. $^1$H NMR spectrum of amine-terminated PMMA (entry 1, table 5.2) in acetone-$d_6$ (200 MHz)

Figure 5.4 shows $^{13}$C NMR spectrum of amine-terminated PMMA’s (entry 1, table 5.2) in acetone-$d_6$. 
Table 5.2. Synthesis of amine end-functional poly (methyl methacrylate) by GTP

<table>
<thead>
<tr>
<th>Entry</th>
<th>MMA, mol</th>
<th>MTS, mol x 10^3</th>
<th>THF, mL</th>
<th>TBABB, mol x 10^3</th>
<th>N-TMS Benzaldimine, mol x 10^3</th>
<th>ZnI_2, mol x 10^3</th>
<th>'BuOH, g/mol</th>
<th>Mn (theory), g/mol</th>
<th>M_n (SEC), g/mol</th>
<th>M_n/ M_w</th>
<th>M_n (VPO), g/mol</th>
<th>M_n (NMR), g/mol</th>
<th>1° efficiency</th>
<th>F°_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.047</td>
<td>2.35</td>
<td>30</td>
<td>2.35</td>
<td>2.35</td>
<td>2.35</td>
<td>2100</td>
<td>2205</td>
<td>1.07</td>
<td>2400</td>
<td>2600</td>
<td>0.95</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.047</td>
<td>1.56</td>
<td>30</td>
<td>1.56</td>
<td>1.56</td>
<td>1.56</td>
<td>3100</td>
<td>3200</td>
<td>1.11</td>
<td>2800</td>
<td>4000</td>
<td>0.97</td>
<td>0.80</td>
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</tr>
<tr>
<td>3</td>
<td>0.047</td>
<td>2.35</td>
<td>30</td>
<td>2.35</td>
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<td>2.35</td>
<td>2100</td>
<td>2525</td>
<td>1.09</td>
<td>2800</td>
<td>3155</td>
<td>0.84</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.047</td>
<td>1.56</td>
<td>30</td>
<td>1.56</td>
<td>1.56</td>
<td>1.56</td>
<td>3100</td>
<td>2905</td>
<td>1.09</td>
<td>3200</td>
<td>3418</td>
<td>1.06</td>
<td>0.85</td>
<td></td>
</tr>
</tbody>
</table>

a: [MMA]_0 = 1.56 mol/L.
b: 1° efficiency = M_n (theory)/M_n (SEC)
c: F°_m = M_n (SEC)/ M_n (NMR)

Figure 5.4. ^13C NMR spectrum of amine-terminated PMMA (entry 1, table 5.2) in acetone-d_6 (50 MHz)
The SEC trace of amine-terminated PMMA (Figure 5.5) (entry 1, Table 5.2) shows a less intense UV-response (due to low concentration of aromatic end-group) at the same elution volume/time of that of RI response indicating the presence of aromatic group at the chain-end.

MALDI-ToF-MS spectrum of amine-terminated PMMA was performed by dissolving the polymer in THF (3 mg/mL) and mixed with the matrix 2,5-dihydroxybenzoic acid (10 mg/mL solution in THF) in a 1:1 proportion. For enhancement of ion formation, a small amount of LiCl was added to the solution. After depositing 0.5 µL of the solution on the sample holder the solvent was evaporated in hot air. MALDI-ToF spectrum of amine-terminated PMMA is shown in figure 5.6 (entry 1, table 5.2) in which the mass peaks correspond to the \([M+Li]^+ = 100.12 \text{ (MMA)} \times n \ \text{(DP)} + H (1.0079) + \text{Ar-CH-NH}_2 (106.1476) + L_+ (6.941)\) for e.g. \(n = 20\) gives \(M_n = 2116.4965\) g/mol i.e., expected series of major fraction will be 2116.4965, 2216.6165, 2316.7365, etc. MALDI ToF exhibited a major series (figure 5.6) as 2109.28, 2209.22, etc with \(\Delta = 7\) Da. Additionally, low intensity peaks attributed to an oligomer series with cyclic end groups \([M+Li]^+ = 100.12 \text{ (MMA)} \times n \ \text{(DP)} + H (1.0079) - \text{OCH}_3 (31) + 6.9(Li)\) for e.g. \(n = 20\) gives \(M_n = 1979.3147\) g/mol i.e., series of lower fraction will be 1979.3147, 2079.4347, 2179.5547, etc. were also observed at mass numbers 1979.21, 2078.86, etc.

Since strong evidence is now present for a dissociative anionic process for GTP\(^2\), the second smaller homologous series (with mass difference between both homologous series is about 31 g/mol due to loss of \(-\text{OCH}_3\) group as a result of backbiting reaction) must be attributed to the
formation of cyclic structure in addition to linear fractions (Scheme 5.4). As the mass increment of both homologous series is the same (i.e. about 100 g/mol of MMA), the change in the chemical structure must be attributed to variations in the end-group.

Scheme 5.4. Formation of cyclic fraction along with amine-terminated PMMA

The fact that both homologous series have their maximum abundance at about 2200 g/mol indicates that they are formed simultaneously in the reaction.

Table 5.3. Different observed series in MALDI ToF MS of amine end-functional PMMA prepared by GTP

<table>
<thead>
<tr>
<th>Polymer</th>
<th>End group</th>
<th>Observed series&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
</table>
| \( \begin{array}{c}
\text{CH}_3 \\
\text{H} - \text{H} - \text{C} - \text{C} - \text{C} - \text{C} - \text{O}_\text{Me}
\end{array} \) | Cyclohexanone end group with \( n = 1 \) i.e. loss of \( -\text{OCH}_3 \) from linear fraction | 1979.21, 2078.86,.... |
| \( \begin{array}{c}
\text{NH}_2 \\
\text{H} - \text{H} - \text{C} - \text{C} - \text{C} - \text{C} - \text{O}_\text{Me}
\end{array} \) | 106.1476 (Ar-CH-NH<sub>2</sub>)-amine end group | 2109.28, 2209.22,...etc with \( \Delta = 7 \text{ Da} \) |

<sup>a</sup> Matrix is 2,5-dihydroxybenzoic acid (F.W: 154.13) with Li+ (LiCl salt)

<sup>b</sup> \([M+Li]^+ = 100.12 \text{ (MMA)} * n \text{ (DP)} + H \text{ (1.0079)} + \text{ Ar-CH-NH}_2 \text{ (106.1476)} + \text{ Li}^+ \text{ (6.941)}\)
This is in accordance with the observation that the living nature of GTP depends on the nature and concentration of catalyst and also on molar mass of the polymer. Here we used 0.1 mol\% of less nucleophilic TBABB catalyst to keep low cyclic fraction. Different observed series in MALDI ToF of amine end-functional PMMA prepared by GTP is shown in table 5.3.

Fig 5.6. MALDI-ToF spectrum of amine-terminated PMMA prepared by GTP using TBABB catalyst for silyl ketene acetal ended PMMA and Lewis acid ZnI₂ for functionalization reaction at room temperature (entry 1, table 5.2). \[ [\text{M+Li}]^+ = 100.12 \text{(MMA)} \times n \text{(DP)} + H (1.0079) + \text{Ar-CH-NH}_2 (106.1476) + \text{Li}^+ (6.941) \]. (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (\( \Delta = 7 \) Da)

5.4 Conclusions

Narrow molecular weight amine-terminated poly (methyl methacrylate) s were prepared by group-transfer polymerization with initiator efficiencies in the range of 0.84-1.06 and narrow molecular weight distributions (\( M_w/M_n = 1.07-1.11 \)). The number average degree of functionalization as determined by NMR/SEC was in the range of 0.80-0.85. MALDI-ToF-MS analysis of amine functionalized PMMA provide evidence for competing chain end cyclization.
High concentration of Lewis acid catalyst (ZnI₂) and long reaction time may result in increased occurrence of cyclization reaction.

5.5 References


