Synthesis of well-defined comb-like amphiphilic copolymers with protonizable units in the pendent chains: 1. Preparation of narrow polydispersity copolymers of methyl methacrylate and 2-hydroxyethyl methacrylate by atom-transfer radical polymerization

Ping Liu, Lan Jin, Jianhua Hu and Changchun Wang

Department of Macromolecular Science, Fudan University and the Key Laboratory of Molecular Engineering of Polymers, Ministry of Education, Shanghai, 200433, People’s Republic of China

Abstract: Well-defined methyl methacrylate (MMA) and 2-(trimethylsiloxy)ethyl methacrylate (Pro-HEMA) copolymers were prepared by atom-transfer radical polymerization (ATRP), using CuCl/2,2'-bipyridine as catalytic system and p-toluenesulfonyl chloride as initiator. ATRP process of MMA and Pro-HEMA was monitored by 1H NMR, and the kinetic curves of the MMA/Pro-HEMA copolymerization were plotted in terms of the 1H NMR data. At low content of Pro-HEMA in the feed composition, the copolymerization can be well controlled with the molecular weight, polydispersity and the monomer distribution in the copolymer chain. With the increase of Pro-HEMA content in the feed mixture, the composition of the final copolymer deviates from the composition of the feed mixture gradually, and gradient copolymers of MMA/Pro-HEMA can be obtained. Through the hydrolysis process, well-defined copolymers of MMA/HEMA were obtained from poly(MMA/Pro-HEMA).

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Keywords: atom-transfer radical polymerization (ATRP); methyl methacrylate; 2-hydroxyethyl methacrylate; 2-(trimethylsiloxy)ethyl methacrylate; copolymers; MMA; HEMA; Pro-HEMA

INTRODUCTION

Macromolecules that have long branches spaced comparatively closely along the main chain are known as comb-like polymers. These copolymers possess a variety of applications, such as impact-resistant plastics, thermoplastic elastomers and compatibilizers. If the comb-like copolymer contains amphiphilic properties, it can accumulate at the interfaces of air and water and may be used as a polymeric surfactant or stabilizer for emulsions or dispersions. The useful properties of comb-like copolymers are afforded by variability in structure through selection of repeat units, copolymer architecture, the length of the main chain and branch chain, etc. In order to obtain more controlled properties, precise control of the structure becomes very important, recent development of the ‘living’ polymerization process gives us more chance to do these.

Atom-transfer radical polymerization (ATRP) is a new ‘living’ free-radical polymerization process, it has been significantly developed in the past several years, and many monomers have been successfully polymerized by ATRP, such as styrene, methyl methacrylate, acrylonitrile and their derivatives with polar or functional groups. It has become a very important method for preparing polymers with well-defined structures, which include molecular weight, mass distribution, functional group. Using ATRP, a many well-defined copolymers have been obtained, such as the copolymers of methyl methacrylate (MMA)/butyl methacrylate, styrene/MMA, MMA/methyl acrylate, MMA/butyl acrylate, styrene/acrylonitrile and styrene/butyl acrylate.

Hydroxyethyl methacrylate (HEMA) is a very useful monomer, the products from which can be used in contact lenses, drug delivery, hydrogels...
and coatings.\textsuperscript{15, 16} Hence, many groups have endeavoured to prepare well-defined copolymers containing HEMA. One approach has used a class of dithioesters to control the random copolymer of HEMA/MMA.\textsuperscript{17, 18} Using ATRP, Matyjaszewski and coworkers\textsuperscript{18, 20} prepared block copolymer and gradient copolymers of HEMA and MMA with well-controlled structures.

In order to prepare well-defined comb-like amphiphilic copolymers, we prepared the well-defined HEMA/MMA copolymers presented in this paper. Because of the polar difference between MMA and HEMA, the well-defined copolymer of HEMA and MMA by ATRP is difficult to prepare directly. So we protected the hydroxyl group of HEMA prior to copolymerization of HEMA and MMA, with a trimethylsiloxy group to give 2-(trimethylsiloxy)ethyl methacrylate (Pro-HEMA). Then well-controlled copolymers of Pro-HEMA and MMA were prepared successfully by ATRP, and the kinetics of the reaction process was monitored by \textsuperscript{1}H NMR. Finally, through the hydrolysis of Pro-HEMA/MMA copolymer, well-defined copolymers of HEMA/MMA were obtained.

\section*{EXPERIMENTAL}
\textbf{Materials}
Methyl methacrylate and cyclohexanone were distilled and stored cold with molecular sieves before use. Pro-HEMA was synthesized according to the literature.\textsuperscript{19} Bipyridine (bpy) was recrystallized in n-hexane and then dried under vacuum. CuCl was purified as follows. 10 g of CuCl powder was completely blended then dried under vacuum. CuCl was purified as follows. 10 g of CuCl powder was completely blended then dried under vacuum. CuCl was purified as follows. 10 g of CuCl powder was completely blended then dried under vacuum. CuCl was purified as follows. 10 g of CuCl powder was completely blended then dried under vacuum. CuCl was purified as follows. 10 g of CuCl powder was completely blended then dried under vacuum.

\textbf{Preparation of poly(MMA-Pro-HEMA)}
Methyl methacrylate/Pro-HEMA copolymers were prepared at 80°C using the following typical procedure. A mixture of bpy (0.226 g, 1.42 \times 10^{-3} \text{ mol}) and CuCl (0.1411 g, 1.42 \times 10^{-3} \text{ mol}) was charged in to a 100-ml round-bottom flask equipped with a magnetic stirrer. The mixture was degassed under vacuum and purged with dry argon. This process was repeated three times, and then MMA (9.5 ml, 0.0892 mol), Pro-HEMA (8.5 ml, 0.0385 \times 10^{-3} \text{ mol}) and cyclohexanone (42 ml), which had been bubbled by argon for at least 1 h, were added into the flask. A fixed amount of p-TsCl was charged in a glass tube, degassed and purged with argon three times, and then dissolved in cyclohexanone. Then, the reaction flask was immersed immediately in a thermostatic bath at 80°C. Samples for kinetic study were taken out and cooled in liquid nitrogen at intervals. A part of the sample was used for NMR measurements to determine the monomer conversion. Another part was passed through a small column of basic aluminum oxide, and then the copolymer solution was precipitated using petroleum ether (boiling range, 60 ~ 90°C). The final copolymer was dried under vacuum at 100°C for 24 h. The polymer composition was determined by \textsuperscript{1}H NMR. Molecular weight and molecular weight distribution were measured by gel permeation chromatography (GPC).

\textbf{Preparation of poly(MMA-co-HEMA)}
The MMA/Pro-HEMA copolymer was dissolved in THF/water under acidic condition at ambient temperature for 24 h, and then precipitated the copolymer in petroleum ether (boiling range, 60 ~ 90°C). The procedure of dissolution and precipitation was repeated three times to completely remove the impurity, and then the copolymer was dried under vacuum at 60°C for 24 h.

\textbf{Gel permeation chromatography (GPC) measurements}
Molecular weight and molecular weight distribution were measured using a GPC instrument HP1100, which was equipped with a Zarbav HX 1618 column connected to a refractive index detector (G1362A) and a UV detector (G1315A) at 35°C. Calibration was carried out with polystyrene standards. THF was used as eluent at a flow rate of 1.0 ml min\textsuperscript{-1}.

\textbf{Nuclear magnetic resonance spectroscopy (NMR) measurements}
Monomer conversion and copolymer composition were determined using their \textsuperscript{1}H NMR spectra. The NMR data were recorded on a DM500 NMR spectrometer at a frequency of 500 MHz with CDCl\textsubscript{3} as solvent.

\textbf{RESULTS AND DISCUSSION}
\textbf{Preparation of poly(MMA/Pro-HEMA)}
Substituted bpy ligands are commonly used in ATRP to increase the solubility of the Cu(I) catalyst. In this paper, unsubstituted bpy was used, because the reaction mixture remained homogeneous in appearance throughout the polymerization in our reaction conditions. As an initiator, p-TsCl can give better control of molecular weight and lower polydispersity for the polymerization of MMA by ATRP,\textsuperscript{21} so that p-TsCl was selected as the initiator in our work. At the beginning of the copolymerization, the appearance of the reaction mixture changed from light reddish brown to green immediately and then turned dark brown after the initiator was charged; this indicated a successful start to the polymerization. Table 1 shows the reagent amounts and results for
Table 1. Reagent amounts and results of atom-transfer radical copolymerization of MMA and Pro-HEMA

<table>
<thead>
<tr>
<th>Sample code</th>
<th>(f_0,\text{MMA})</th>
<th>(M_n \times 10^3) (g mol(^{-1}))</th>
<th>(M_n/M_w)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-1</td>
<td>0.893</td>
<td>10.8</td>
<td>1.05</td>
<td>96.8</td>
</tr>
<tr>
<td>MP-2</td>
<td>0.693</td>
<td>12.3</td>
<td>1.08</td>
<td>74.1</td>
</tr>
<tr>
<td>MP-3</td>
<td>0.670</td>
<td>8.8</td>
<td>1.12</td>
<td>95.4</td>
</tr>
<tr>
<td>MP-4</td>
<td>0.503</td>
<td>15.9</td>
<td>1.25</td>
<td>83.7</td>
</tr>
</tbody>
</table>

\(^a\) The solvent is cyclohexanone; monomer/solvent (v/v) = 3/7; reaction temperature is 80 \(^\circ\)C; \([\text{M}]_0 : [\text{I}]_0 : [\text{CuCl}]_0 : [\text{bpy}]_0 = 90:1:1:1.

the copolymerization of MMA and Pro-HEMA with different initial feed compositions.

Monomer conversion is often determined from the concentration of residual monomer using GC, but for a monomer with a high boiling point which may be unstable, such as Pro-HEMA (50 \(^\circ\)C/0.06 Torr), use of \(^1\)H NMR may be more suitable. In this paper, we monitored the kinetic data of copolymerization of Pro-HEMA and MMA by \(^1\)H NMR. Figure 1 shows the \(^1\)H NMR spectra of reaction solutions at different reaction times. During the polymerization, it is seen that the intensities of vinyl signals (\(\delta_a = 5.58, 6.12\) ppm) of monomer decreased gradually. Even at the high conversation level, the peak area of the vinyl signal can also be obtained very well (at high-yield level, we used the new signal of –CH\(_2–\), \(\delta_b = 0.8\) ppm in the polymer backbone to check the calculate results), and this indicated that we can use this method to monitor the polymerization process.

Using the \(^1\)H NMR data, we can calculate the total monomer conversion (\(\text{Con}_{\text{total}}\)) from the signal of the double-bond protons (\(\delta_a = 5.5, 6.2\) ppm).

\[
\ln \frac{[\text{M}_0]}{[\text{M}_n]} = \ln \frac{A_0}{A_n} \\
\text{Con}_{\text{total}} = 1 - \frac{[\text{M}_n]}{[\text{M}_0]} = 1 - \frac{A_n}{A_0}
\]

where \(A_n = \frac{D_{\text{ethyl}}}{D_{\text{TMS}}}, D_{\text{ethyl}}\) and \(D_{\text{TMS}}\) are peak areas of the double-bond and TMS in the NMR spectra, respectively. \(A_0\) is the normalized peak areas of double-bond in NMR spectra; here \(A_0 = D_{\text{ethyl}}/D_{\text{TMS}}\)

The copolymer compositions are calculated from the \(^1\)H NMR spectra of pure copolymer (Fig 2), the

![Figure 1. \(^1\)H NMR spectra of ATRP solution (\(f_0,\text{MMA} = 0.670\)) at different reaction times.]

The signal of trimethylsilyl (TMS) protons (\(\delta_b = 0.06–0.16\) ppm) of Pro-HEMA was used as standard.

![Figure 2. \(^1\)H NMR spectrum of MMA/Pro-HEMA copolymer (MP-3).]
Calculation equations are as follows:

\[ F_{\text{cum}, \text{MMA}} = \frac{D_{\text{MMA}}/8}{D_{\text{MMA}}/8 + D_{\text{pro-H}}/18} \]  

\[ \text{Con}_{\text{MMA}} = \frac{\text{Con}_{\text{total}} \times F_{\text{cum}, \text{MMA}}}{f_{0, \text{MMA}}} \]  

\[ \text{Con}_{\text{pro-H}} = \frac{\text{Con}_{\text{total}} \times (1 - F_{\text{cum}, \text{MMA}})}{f_{0, \text{pro-H}}} \]

where \( D_{\text{MMA}} = D_{\text{total}} - D_{\text{pro-H}} \), \( D_{\text{MMA}} \) and \( D_{\text{pro-H}} \) are peak areas of the total proton signals of MMA and Pro-HEMA in the copolymer, respectively; \( D_{\text{total}} \) is the total area of pure copolymer in \(^1\)H NMR spectra; \( F_{\text{cum}, \text{MMA}} \) is the average molar ratio of MMA unite in the whole polymer chain, and \( f_{0, \text{MMA}} \) and \( f_{0, \text{pro-H}} \) are initial compositions of MMA and Pro-H in the feed monomers, respectively, which were calculated from the \(^1\)H NMR spectra of initial reaction solution. These were calculated by the follow equations:

\[ f_{0, \text{MMA}} = 1 - \frac{D_{0, \text{TMS}}/9}{D_{0, \text{ethyl}}/2} \]  

\[ f_{0, \text{pro-H}} = \frac{D_{0, \text{TMS}}/9}{D_{0, \text{ethyl}}/2} \]

Figure 3 shows the plot of \( \ln([M]/[M]) \) versus time for copolymer of MMA and Pro-HEMA. From this figure, we can see that, with the increase of Pro-HEMA content in the feed mixture, the irreversible termination increase, and the experimental data deviated from the theoretical. This may due to the side-reaction of Pro-HEMA. The similar results have been reported by Matyjaszewskii in the homopolymerization of Pro-HEMA.

The plots of monomer conversion versus time were showed in Figs 4 to 6. From these figures, we find that more than 95% of MMA was consumed at the end of polymerization, and only about 60–80% Pro-HEMA was consumed. These results indicate that the reactivity of MMA and Pro-HEMA in ATRP is different. With the increase of Pro-HEMA content in the feed mixture, the overall polymerization rate
decreases quickly and the polymerization process was retarded. After 30 h of polymerization, the yield was only 83.7% for the \( f_0,\text{MMA} = 0.503 \) system, but the conversion could reach to 96.8% after 12 h polymerization for the \( f_0,\text{MMA} = 0.893 \) system. Figure 7 demonstrates that the MMA content in the resulting polymer is higher than the original feed composition, especially for the high Pro-HEMA content system and at the beginning of the polymerization. For the high Pro-HEMA content system, the composition of the produced copolymer changed gradually with the increase of the monomers conversion. The above result suggests that, through this process, the gradient copolymer of MMA/Pro-HEMA can be obtained by ATRP.

Figures 8–10 show the dependence of molecular weight and molecular weight distribution on conversion. A linear relationship between molecular weight and conversion can be seen in Fig 8, and the molecular weight polydispersity is quite narrow. With the increase of Pro-HEMA content in the feed composition, the molecular weight deviated from a straight line above about 50% conversion, and the molecular weight polydispersity also deviated from the conventional ATRP tendency (see Figs 9 and 10) dramatically. This means the ATRP process may be out of precise control when MMA is used up, and the molecular weight polydispersity is also tending to broaden at the same time.

**Hydrolysis of poly(MMA/HEMA)**

All copolymers of MMA and HEMA were prepared by hydrolysis of poly(MMA/Pro-HEMA) in THF/H\(_2\)O solution under acidic condition. The \(^1\)H NMR spectra of poly(MMA/Pro-HEMA) \((f_0,\text{MMA} = 0.670)\) and its hydrolysis product are shown in Fig 11. Comparison of the spectra of poly(MMA/Pro-HEMA) and Poly(MMA/HEMA), shows that the peak of trimethylsiloxy(TMS) protons \((\sim 0.16 \text{ ppm})\) disappeared completely in the spectra of poly(MMA-co-HEMA), and the methyl ester peak of MMA \((\sim 3.6 \text{ ppm})\) and the ethyl ester peak of HEMA \((\sim 3.8 \text{ ppm}, \sim 4.1 \text{ ppm})\) became clearer. This result indicated that MMA/HEMA copolymer is obtained and the hydrolysis reaction is quite efficient using these copolymers. The preparation of comb-like amphiphilic copolymers will be described in our next paper.

**CONCLUSIONS**

Well-defined copolymers of MMA/Pro-HEMA were prepared in cyclohexanone at 80 °C using CuCl/bpy
as catalyst and $\rho$-TSCl as initiator. When the MMA content is high in the feed mixture, a first-order kinetic plot can be obtained, and the molecular weight polydispersity ($M_w/M_n$) is low at 1.1. With the increase of the Pro-HEMA content in the feed mixture, the composition of the final copolymers deviated from the composition of the feed mixture gradually, and gradient copolymers of MMA/Pro-HEMA can be obtained. Using ATRP, well-controlled copolymers of poly(MMA-co-Pro-HEMA) can be obtained. Through this hydrolysis process, well-defined copolymers of MMA/HEMA were obtained.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation of China (Grant No 50173005) and Association of Shanghai Science and Technology.

REFERENCES