Preparation of Comb-Like Copolymers with Amphiphilic Poly(ethylene oxide)-*b*-polystyrene Graft Chains by Combination of ''Graft From'' and ''Graft Onto'' Strategies

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ABSTRACT: A novel method for preparation the comb-like copolymers with amphihilic poly(ethylene oxide)-block-poly(styrene) (PEO-*b*-PS) graft chains by "graft from" and "graft onto" strategies were reported. The ring-opening copolymerization of ethylene oxide (EO) and ethoxyethyl glycidyl ether (EEGE) was carried out first using α-methoxyl-ω-hydroxyl-poly(ethylene oxide) (*m*PEO) and diphenylmethyl potassium (DPMK) as coinitiation system, then the EEGE units on resulting linear copolymer *m*PEO-*b*-Poly(EO-*co*-EEGE) were hydrolyzed and the recovered hydroxyl groups were reacted with 2-bromoisobutyryl bromide. The obtained macroinitiator *m*PEO-*b*-Poly(EO-*co*-BiBGE) can initiate the polymerization of styrene by ATRP via the "Graft from" strategy, and the comb-like copolymers *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS] were obtained. Afterwards, the TEMPO-PEO was prepared by ring-opening polymerization (ROP) of EO initiated by 4-hydroxyl-2,2,6,6-tetramethyl piperdinyl-oxy (HTEMPO) and DPMK, and then coupled with *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS] by atom transfer nitroxide radical coupling reaction in the presence of cuprous bromide (CuBr)/*N,N,N',N'',N''*-pentamethyldiethylenetriamine (PMDETA) via "Graft onto" method. The comb-like block copolymers *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-(PS-*b*-PEO)] were obtained with high efficiency (≥90%). The final product and intermediates were characterized in detail. © 2009 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 47: 1930–1938, 2009

Keywords: atom transfer nitroxide radical coupling; atom transfer radical polymerization (ATRP); block copolymers; graft copolymer; ring-opening polymerization; 2,2,6,6-tetramethylpiperidine-1-oxyl

INTRODUCTION

Over the past several decades, block copolymers consisting of one or more hydrophilic blocks covalently connected to a series of hydrophobic blocks have attracted considerable attention.[1] These amphiphilic grafting copolymers were widely used in biomedical materials,[2,3] nanotechnology,[4] composite polymer materials,[5] and supramolecular science[6] based on their individual structure and properties. On the other hand, the rapid progress in polymerization methods, such as the "living" anionic polymerization,[7] nitroxide-mediated radical polymerization (NMRP),[8] Atom-transfer radical polymerization (ATRP)[9] and others in a "living"/controlled manner, have also made it possible to prepare well-defined copolymers with

complicated structure in molecular level. By combination of these mechanisms with synthesis strategies ("grafting from," "grafting onto," and "grafting through"), a variety of grafting copolymers with different structure have been prepared.

The amphiphilic graft copolymers containing poly(ethylene oxide) (PEO) was a very important field in polymer chemistry because of the good solubility in many solvents, biocompatibility, and other special properties for PEO. The preparation of graft copolymers containing PEO segments has been reviewed by Xie and Xie[10], and Borner and Matyjaszewski[11]; however, the graft copolymers with amphiphilic side chains containing PEO block were rarely reported because of the modification difficulty of PEO functional end group,[12] as well as the low DP of the diblock macromonomers contained PEO subchain.[13]

Recently, a new strategy termed as atom transfer nitroxide radical coupling (ATNRC) reaction was reported by our group,[14,15] in this system, bimolecular termination generated by the macroradicals in ATRP would be restricted, and the radicals formed in the ATRP was trapped by nitroxide radicals as 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) or TEMPO derivatives instantly, and the coupling reaction between bromide end groups and TEMPO groups was carried out in the presence of CuBr/PMDETA catalyst.

Herein, to introduce the PEO segment into the grafting copolymers, the comb-like copolymers with amphiphilic PS-b-PEO graft chains was prepared by the combination of "graft from" via ATRP and "graft onto" via ATNRC reaction. The final product mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)] with high efficiency was obtained.

EXPERIMENTAL

Materials

Ethoxyethyl glycidyl ether (EEGE) was prepared according to literature.[16] Ethylene oxide (EO, Sinopharm Chemical Reagent Co., Ltd (SCR), 98%) was dried with calcium hydride (CaH$_2$) for 48 h and then distilled before use. Tetrahydrofuran (THF, SCR, 99%) and pyridine (SCR, 99.5%) were refluxed over sodium wire and then distilled from sodium naphthalenide and sodium wire solution, respectively. Styrene (St, Aldrich, 98%) was washed with 10% NaOH aqueous solution followed by water three times successively, dried over CaH$_2$, and distilled under reduced pressure. Dimethyl sulfoxide (DMSO, SCR, 98%) was dis-

tilled over CaH$_2$ under reduced pressure just before use. Cuprous bromide (CuBr, Acros, 98%) was purified by stirring overnight in acetic acid and filtered, then washed with ethanol and diethyl ether successively, and finally dried under vacuum. 2-Bromoisobutyryl bromide (98%), glycidol, 2,2′-bipyridyl (bpy) and PMDETA were purchased from Aldrich and used as received. Diphenylmethyl potassium (DPMK) solution was freshly prepared by the reaction of potassium naphthalenide with diphenylmethane in THF according to the literature,[17] the concentration was 0.57 mol/L. 4-Hydroxyl-2,2,6,6-tetramethylpiperidinyl-1-oxy (HTEMPO) was synthesized according to the literature.[18] α-Methoxyl-ω-hydroxy-poly(ethylene oxide) (mPEO, $M_{n(SEC)}$ = 7800 g/mol, PDI = 1.10) was synthesized by ROP of EO using ethylene glycol monomethyl ether potassium as the initiator. TEMPO-PEO ($M_{n\ (SEC)}$ = 3700 g/mol, PDI = 1.09) was synthesized according to a previous work using HTEMPO and DPMK as coinitiator, and ^{1}H NMR spectrum was recorded in the presence of calculated amount of ammonium formate and palladium-on-carbon using CD$_3$OD as solvent, δ (ppm): 1.15–1.18 (—CH_3 of TEMPO group), 1.45 and 1.95 (—CH_2— of TEMPO group), 3.36–3.75 (—CH_2CH$_2$O— of PEO chain).[19]

Measurements

The number-average molecular weight and polydispersity index (PDI) were estimated by size exclusion chromatography (SEC). For the TEMPO-PEO and mPEO, SEC traces were performed in 0.1 M NaNO$_3$ aqueous solution at 40 °C with an elution rate of 0.5 mL/min on an Agilent 1100 equipped with a G1310A pump, a G1362A refractive index detector, and a G1315A diode-array detector. Three TSKgel PW columns in series (molecular weight ranges of 0 to 5 × 10^4, 5 × 10^4 to 8 × 10^6, and 5–8 × 10^6 g/mol, respectively) were calibrated with PEO standard samples. SEC traces of the rest (co)polymers were performed in THF at 35 °C with an elution rate of 1.0 mL/min on an Agilent1100 with a G1310A pump, a G1362A refractive index detector, and a G1314A variable wavelength detector. One 5-μm LP gel column (500 E, molecular range 500 to 2 × 10^4 g/mol) and two 5-μm LP gel mixed bed column (molecular range 200 to 3 × 10^6 g/mol) were calibrated by polystyrene standard samples. ^{1}H NMR spectra were obtained by a DMX 500 MHz spectrometer using tetramethyl silane (TMS) as the

internal standard and CDCl$_3$ as the solvent. The ultra filtration membrane separator was purchased from Shanghai Institute of Applied Physics, Chinese Academy of Science, the cut-off molecular weight of used poly(ether sulfone) film: $M_{w(cut-off)}$ = 6000 g/mol, 10,000 g/mol, 20,000 g/mol (calibrated by globe protein).

Synthesis of Linear Copolymer Methoxyl Poly(ethylene oxide)-*b*-poly(ethylene oxide-*co*-ethoxyethyl glycidyl ether) (*m*PEO-*b*-Poly(EO-*co*-EEGE))

The anionic ring-opening copolymerization of EO and EEGE was carried out in an ampoule, using *m*PEO ($M_{n(SEC)}$ = 7800 g/mol) and DPMK as coinitiators. First, *m*PEO (13.0 g, 1.67 mmol) was dried by azeotropic distillation with toluene and dissolved in 100 mL mixed solvents of DMSO and THF (v/v = 1/9), then the required amount (4.5 mL, 0.5 M solution) of DPMK was added. After the addition of EEGE (6.0 g, 41.1mmol) and the cold EO (5.0 mL), the ampoule was immersed into an oil bath and heated to 50 °C and stirred for 48 h. The product was purified by dissolution/precipitation with methylene chloride/ethyl ether thrice, dried *in vacuo* at 40 °C for 24 h.

^{1}H NMR (CDCl$_3$) δ (ppm): 1.20(C$\boldsymbol{H}_3$CH$_2$—), 1.30 (—CH(C$\boldsymbol{H}_3$)—), 3.38(C$\boldsymbol{H}_3$O—), 3.45–3.74 (—C$\boldsymbol{H}_2$CH$_2$O—, —C$\boldsymbol{H}_2$CH(C$\boldsymbol{H}_2$—)O— for PEO main chain and —C$\boldsymbol{H}_2$OCH(CH$_3$)OC$\boldsymbol{H}_2$CH$_3$—, for EEGE side chain), 4.70 (—C$\boldsymbol{H}$(CH$_3$)—), $M_{n(NMR)}$ = 11,300 g/mol. SEC: $M_{n(SEC)}$ = 9500 g/mol, PDI = 1.19.

Synthesis of Linear Copolymer Methoxyl Poly(ethylene oxide)-*b*-poly(ethylene oxide-*co*-glycidyl) (*m*PEO-*b*-Poly(EO-*co*-Gly)) by the Cleavage of the Ethoxyethyl Groups

The hydrolysis procedure of the copolymer *m*PEO-*b*-Poly(EO-*co*-EEGE) was carried out according to literature.[20] *m*PEO-*b*-[Poly(EO-*co*-EEGE)] ($M_{n(NMR)}$ = 11,300 g/mol, 15.0 g, 1.33 mmol) was mixed with formic acid (70 mL), the solution was stirred at room temperature for 30 min and then evaporated *in vacuo* at 50 °C to remove formic acid. The obtained crude product was then dissolved in a mixture of dioxane (100 mL) and methanol (50 mL) and saponified by KOH aqueous solution (1.0 mol/L, 20 mL) under refluxing for 24 h, and then neutralized with HCl aqueous solution (1.0 mol/L). After all the solvents were removed under reduced pressure, the remains were dissolved in methylene chloride and

the formed salts were removed by filtration. The product was obtained by precipitation with ethyl ether and purified by dissolution/precipitation with methylene chloride/ethyl ether.

^{1}H NMR (CDCl$_3$) δ (ppm): 3.38 (C$\boldsymbol{H}_3$O—), 3.54–3.79 (—C$\boldsymbol{H}_2$CH$_2$O—, —C$\boldsymbol{H}_2$CHO— for PEO main chain and —C$\boldsymbol{H}_2$OH for Gly side chain), $M_{n(cal.)}$ = 10,100 g/mol.

Preparation of Macroinitiator Methoxyl Poly(ethylene oxide)-*b*-[poly(ethylene oxide-*co*-2-bromoisobutyryloxy glycidyl ether)] (*m*PEO-*b*-Poly(EO-*co*-BiBGE))

*m*PEO-*b*-[Poly(EO-*co*-Gly)] ($M_{n(cal.)}$ = 10,100 g/mol, 10 g, 17 mmol hydroxyl groups) was dried by azeotropic distillation with toluene and dissolved in anhydrous pyridine (100 mL), to which 2-bromoisobutyryl bromide (3.0 mL, 24.43 mmol) was added dropwise at 0 °C over 30 min under vigorous stirring, followed by stirring at room temperature overnight. Afterwards, pyridine was distilled under reduced pressure, and then the residual was washed with cyclohexane three times and dialyzed against deionized water to ensure all the impurities were moved out. After removal of the water, transparent and viscous *m*PEO-*b*-Poly(EO-*co*-BiBGE) with a pale yellow color was obtained and dried *in vacuo* at 35 °C for 24 h.

^{1}H NMR (CDCl$_3$) δ (ppm): 1.93 (—C(C$\boldsymbol{H}_3$)$_2$Br), 3.38 (C$\boldsymbol{H}_3$O—), 3.49–3.79 (—C$\boldsymbol{H}_2$CH$_2$O— and —C$\boldsymbol{H}_2$CH(CH$_2$—)O— for PEO main chain), 4.19–4.35 (—C$\boldsymbol{H}_2$COO—), $M_{n(cal.)}$ = 12,800 g/mol.

Synthesis of Comb-Like Copolymers Methoxyl Poly(ethylene oxide)-*b*-[poly(ethylene oxide-*co*-glycidyl)-*g*-polystyrene] (*m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS]) by ATRP

The synthesis of *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS1] is presented as an example. 1.0 g macroinitiator *m*PEO-*b*-[Poly(EO-*co*-BiBGE)] ($M_{n(cal.)}$ = 12,800 g/mol, 0.663 mmol of bromoisobutyryl groups), CuBr (0.095 g, 0.663 mmol), bpy (0.207 g, 0.663 mmol), and styrene (16 mL, 130mmol) were placed in an ampoule and degassed with three cycles of freeze–pump–thaw. The sealed ampoule was immersed into an oil bath at 90 °C. After 1 h, the ampoule was quenched in liquid nitrogen and exposed to air, and the crude products were dissolved in THF and filtered through a short column of neutral alumina to remove copper salts. The crude product was purified thrice by dissolution/precipitation with methylene chloride/

methanol, and a white powder mPEO-b-[Poly (EO-co-Gly)-g-PS1] was obtained and dried *in vacuo* at 40 °C for 24 h.

^{1}H NMR (CDCl$_3$) δ (ppm): 0.77–0.81(—C(C$\textbf{\textit{H}}_3$)$_2$—), 1.31–1.98(—C$\textbf{\textit{H}}_2$CH(Ph)—), 3.31 (C$\textbf{\textit{H}}_3$O—), 4.30–4.50 (—C$\textbf{\textit{H}}$(Ph)Br), 4.49–4.69 (—C$\textbf{\textit{H}}_2$CH$_2$O— and —C$\textbf{\textit{H}}_2$CHO— for PEO main chain), 6.31–7.01 (—C$_6\textbf{\textit{H}}_5$—) $M_{n(\text{NMR})}$ = 63,200 g/mol. SEC: $M_{n(\text{SEC})}$ = 18,000 g/mol, PDI = 1.09.

Preparation of Comb-Like Block Copolymers Methoxyl Poly(ethylene oxide)-*b*-[poly(ethylene oxide-*co*-glycidyl)-*g*-(polystyrene-*b*-poly(ethylene oxide))] (*m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-(PS-*b*-PEO)]) by ATNRC

Typically, mPEO-b-[Poly(EO-co-Gly)-g-PS1] ($M_{n(\text{NMR})}$ = 63,200 g/mol, 0.8 g, 0.23 mmol of Br atoms), TEMPO-PEO ($M_{n(\text{SEC})}$ = 3700 g/mol, 1.0 g, 0.28 mmol), toluene (20 mL), CuBr (0.033 g, 0.23 mmol), and PMDETA (0.046 mL, 0.23 mmol) were charged in a 50 mL ampoule. The reaction mixture was degassed with three cycles of freeze–pump–thaw and then purged with N$_2$, kept at 90 °C for 48 h. Afterwards, the mixture was diluted with THF and passed through an activated neutral alumina column to remove the copper salts. After THF was removed by distillation under vacuum, the crude product was dissolved in methanol and purified by an ultrafiltration membrane to remove the remaining TEMPO-PEO. The product mPEO-b-[Poly(EO-co-Gly)-g-(PS1-b-PEO)] was concentrated and then dried in vacuum at 45 °C for 12 h till to a constant weight.

^{1}H NMR (CDCl$_3$) δ (ppm): 0.86–0.88 (—C(C$\textbf{\textit{H}}_3$)$_2$—), 1.10–1.98 (—C$\textbf{\textit{H}}_2$CH(Ph)—, —C$\textbf{\textit{H}}_3$ of TEMPO group, —C$\textbf{\textit{H}}_2$— of TEMPO group and —C$\textbf{\textit{H}}$— of TEMPO group), 3.38 (C$\textbf{\textit{H}}_3$O—), 3.49–3.69 (—C$\textbf{\textit{H}}_2$CH$_2$O—, —C$\textbf{\textit{H}}_2$CHO— for PEO main chain and side chain), 6.45–7.08 (—C$_6\textbf{\textit{H}}_5$—). SEC: $M_{n(\text{SEC})}$ = 9000, PDI = 1.05.

Graft Side Chains Cleavage from *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS] and *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-(PS-*b*-PEO)]

Typically, mPEO-b-[Poly(EO-co-Gly)-g-PS] ($M_{n(\text{NMR})}$ = 63,200 g/mol, 0.3 g, 0.005 mmol) was dissolved in THF (50 mL), to which KOH solution (10 mL, 1.0 M in ethanol) was added and the mixture was refluxed for 48 h. After filtrating the salts, the solution was precipitated in methanol, the solid product PS1 was purified thrice by dissolution/precipitation with methylene chloride/

methanol and dried at 50 °C for 24 h. SEC: $M_{n(\text{SEC})}$ = 2800 g/mol, PDI = 1.15.

Similarly, mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)] was also treated using aforementioned procedure and the cleaved product PS1-b-PEO was purified by dissolution/precipitation thrice with chloroform/petroleum ether and dried at 50 °C for 24 h.

^{1}H NMR (CDCl$_3$) δ (ppm): 0.86–0.88 (—C(C$\textbf{\textit{H}}_3$)$_2$—), 1.02–1.89 (—C$\textbf{\textit{H}}_2$CH(Ph)—, —C$\textbf{\textit{H}}_3$ of TEMPO group, —C$\textbf{\textit{H}}_2$— of TEMPO group and —C$\textbf{\textit{H}}$— of TEMPO group), 3.50–3.78 (—C$\textbf{\textit{H}}_2$CH$_2$O—, —C$\textbf{\textit{H}}_2$CHO— for PEO chain), 6.59–7.06 (—C$_6\textbf{\textit{H}}_5$—). SEC: $M_{n(\text{SEC})}$ = 6400, PDI = 1.11.

RESULTS AND DISCUSSION

Synthesis of Macroinitiator *m*PEO-*b*-Poly(EO-*co*-BiBGE) for "Graft From" Strategy

As Scheme 1 showed that the mPEO-b-Poly(EO-co-BiBGE) for "Graft from" strategy was synthesized by a series of reactions including preparation of precursor copolymer mPEO-b-Poly(EO-co-EEGE) and then modification. In the first step, the anionic ring-opening copolymerization of EO and glycidol was carried out using mPEO and DPMK as the coinitiator system in the mixed solvents of THF and DMSO, and the monomer glycidol should be protected by ethyl vinyl ether (which is termed as EEGE) because of the exchange reaction between the hydroxyl group of glycidol and DPMK.[21]

The molecular weight and PDI of mPEO-b-Poly (EO-co-EEGE) copolymer were measured by SEC, and the PDI was rather narrow (see the Experimental part). Comparing with its prepolymer mPEO ($M_{n(\text{SEC})}$ = 7,800 g/mol), an obvious increase of the molecular weight was observed. However, considering the amphiphilicity of the block copolymer and the micelle would be formed,[22] the M_n obtained by SEC using THF as eluent may be inaccurate. Thus, M_n was also calculated from the spectrum of ^{1}H NMR.

The ^{1}H NMR spectrum of mPEO-b-Poly(EO-co-EEGE) was shown in Figure 1(A). The quadruplet at δ = 4.70 ppm was ascribed to the methine protons (—OC$\textbf{\textit{H}}$(CH$_3$)O—) of the ethoxy ethyl groups in EEGE units, the protons of the two different methyl groups in the EEGE units appeared at δ = 1.30 ppm (—OCH(C$\textbf{\textit{H}}_3$)O—) as a doublet and at δ = 1.20 ppm (—OCH$_2$C$\textbf{\textit{H}}_3$) as a triplet, respectively. The signal of methylene protons in lateral
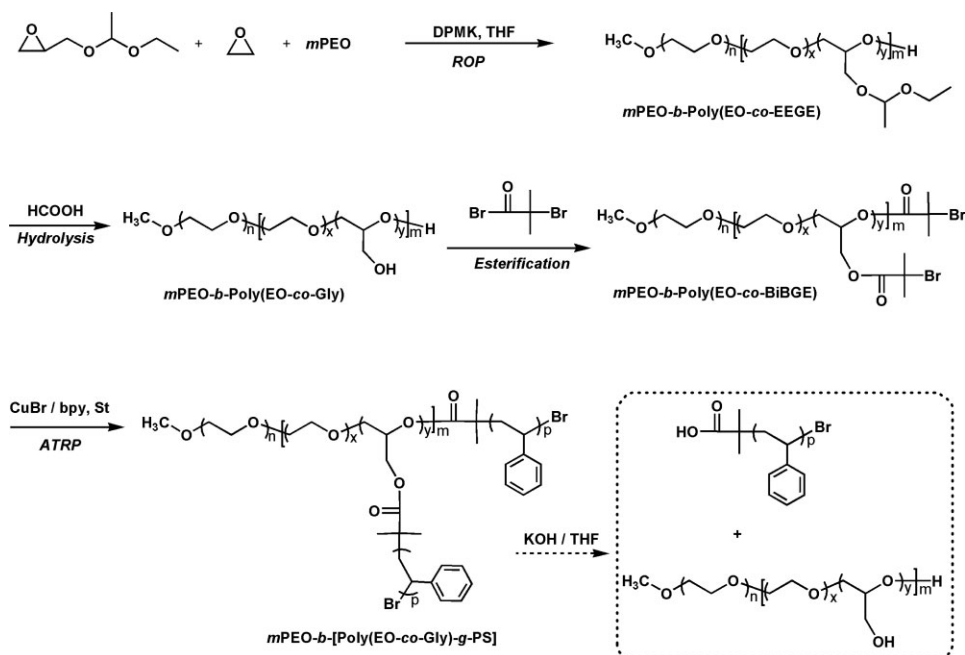
Scheme 1. The synthesis procedure of comb-like block copolymers *m*PEO-*b*-[Poly-(EO-*co*-Gly)-*g*-PS] and their cleavage.

chains and the methylene or methine protons in main chain were in the range of $\delta = 3.45$–3.75 ppm, and the methyl protons at the PEO end were detected at 3.38 ppm. The number of EEGE ($N_{\text{EEGE}} = 17$) in *m*PEO-*b*-Poly(EO-*co*-EEGE) and the number-average molecular weight ($M_{n(\text{NMR})(m\text{PEO-}b\text{-Poly(EO-}co\text{-EEGE}))} = 11,300$ g/mol) could be calculated by the following equation eqs 1 and 2, respectively:

$$N_{\text{EEGE}} = \frac{3A_d}{A_a} \qquad (1)$$

$$M_{n(\text{NMR})(m\text{PEO-}b\text{-Poly(EO-}co\text{-EEGE}))}$$
$$= \frac{\dfrac{A_{b,c,f} - 7A_d}{4} \times 44 + A_d \times 146}{\dfrac{A_a}{3}} \qquad (2)$$

where $A_{b,c,f}$, A_d, and A_a were the integral areas of corresponding protons in ^{1}H NMR [Fig. 1(A)], 146 and 44 were the molecular weight of EEGE and EO unit, respectively. Approximately, the monomer ratio of EO to EEGE was 1:1 on the main chain.

The *m*PEO-*b*-Poly(EO-*co*-EEGE) was treated with formic acid first and then the produced poly-formate was further saponified in the KOH dioxane/methanol mixture solution, and the hydroxyl groups were recovered. Thus, the *m*PEO-*b*-Poly-(EO-*co*-EEGE) was transformed to *m*PEO-*b*-Poly-

(EO-*co*-Gly) with multipending hydroxyl groups. The complete removal of the ethoxyethyl groups was confirmed by ^{1}H NMR analysis. The peaks at $\delta = 4.70$ ppm, at $\delta = 1.30$ ppm and at $\delta = 1.20$ ppm assigned to the ethoxyethyl group of *m*PEO-*b*-Poly(EO-*co*-EEGE) in Figure 1(A) disappeared completely after hydrolysis [Fig. 1(B)]. The number-average molecular weight of *m*PEO-*b*-
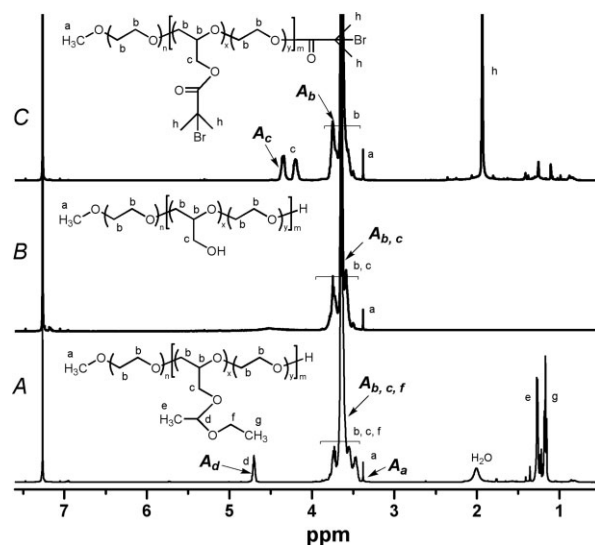

Figure 1. ^{1}H NMR spectra of *m*PEO-*b*-Poly(EO-*co*-EEGE) (A), *m*PEO-*b*-Poly(EO-*co*-Gly) (B), and *m*PEO-*b*-Poly(EO-*co*-BiBGE) (C).

Poly(EO-*co*-Gly) $(M_{n(\text{cal.})[m\text{PEO-}b\text{-Poly(EO-}co\text{-Gly})]} = 10,100$ g/mol) could be calculated by eq 3:

$$M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-Gly}))}$$
$$= M_{n(\text{NMR})(m\text{PEO-}b\text{-Poly(EO-}co\text{-EEGE}))}$$
$$- 72 \times N_{\text{EEGE}} \quad (3)$$

where 72 was the molecular weight of ethoxyethyl group, while the others were the same as before.

After the reaction of the multipendant hydroxyl groups of *m*PEO-*b*-Poly(EO-*co*-Gly) with 2-bromoisobutyryl bromide, macroinitiators *m*PEO-*b*-Poly(EO-*co*-BiBGE) were obtained. The purification procedure was carried out according to the literature,[23] no trace of pyridine salts and small molecule impurities were detected by ^{1}H NMR spectrum after purification. The complete esterification of the hydroxyl groups on *m*PEO-*b*-Poly(EO-*co*-Gly) could also be confirmed by ^{1}H NMR in Figure 1(C), the conversion efficiency(EF) of hydroxyl group and the number-average molecular weight of *m*PEO-*b*-Poly(EO-*co*-BiBGE) $(M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-BiBGE})]})$ (12,800 g/mol) could be calculated by eqs 4 and 5, respectively:

$$\text{EF} = \frac{\dfrac{A_\text{d}}{2}}{\dfrac{A_\text{a}}{3} \times (N_{\text{EEGE}} + 1)} \times 100\% \quad (4)$$

$$M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-BiBGE}))}$$
$$= M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-Gly}))}$$
$$+ 148 \times (N_{\text{EEGE}} + 1) \quad (5)$$

where A_a and A_d were the integral areas in ^{1}H NMR (Fig. 1C). The value of EF was nearly 100%, which proved the esterification was really complete.

Synthesis of Comb-Like Copolymers *m*PEO-*b*-[(Poly(EO-*co*-Gly)-*g*-PS)] by "Graft from" Strategy

To ensure the successful coupling reaction in next ATNRC, the ATRP of styrene using macroinitiator *m*PEO-*b*-Poly(EO-*co*-BiBGE) by "Graft from" strategy could only be conducted in limited conversions (<35%) to obtain a high degree of bromines at chain ends,[24] otherwise the gel was formed. In our system, the St monomer conversion was controlled below 20%, the bpy and CuBr were used as the catalyst. The obtained grafting copolymer *m*PEO-*b*-[(Poly(EO-*co*-Gly)-*g*-PS)] showed the monomodal SEC curve [Fig. 2(D)], and the polydispersity in all cases were low (PDI < 1.2) (Table 1)
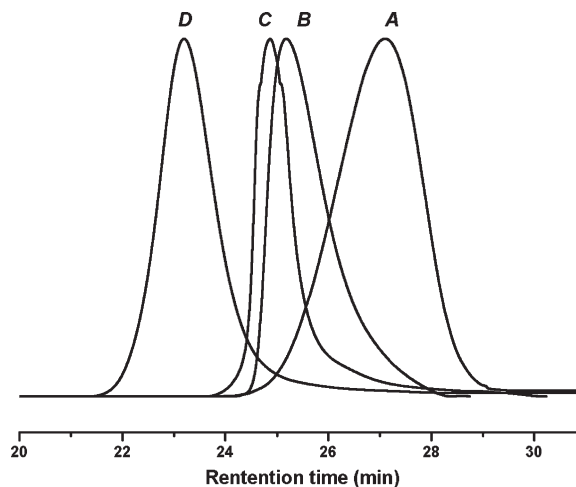
Figure 2. SEC curves of cleaved PS1 (A), cleaved PS1-*b*-PEO (B), *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-(PS1-*b*-PEO)), (C) *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS1] (D).

Figure 3(B) shows the ^{1}H NMR spectrum of the grafting copolymer *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS]. The signal at $\delta = 4.28$–4.65 ppm was attributed to end methine protons ($-\text{C}\boldsymbol{H}\text{Br}$), the signal at $\delta = 6.33$–7.31 ppm was assigned to the protons ($-\text{C}_6\boldsymbol{H}_5$) of PS chains, and the signal at $\delta = 3.44$–3.79 ppm was assigned to the protons of the *m*PEO-*b*-Poly(EO-*co*-Gly) main chain. The peaks at 1.93–1.99 ppm for methyl groups close to the Br atom was shifted to higher field (0.89–0.97 ppm) because of the change of the carbon–bromine bond to the carbon–carbon bond of the tertiary carbon. These changes confirmed that the ATRP was successful, and all the initiating sites on *m*PEO-*b*-Poly(EO-*co*-BiBGE) were served in ATRP, which was similar to the result reported by Li et al.[25]

The number-average molecular weight of *m*PEO-*b*-[Poly(EO-*co*-Gly)-*g*-PS] $M_{n(\text{NMR})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly})\text{-}g\text{-PS}])}$ could be calculated by eq 6 and the obtained data were listed in Table 1.

$$M_{n(\text{NMR})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly})\text{-}g\text{-PS}])}$$
$$= \frac{A_\text{m}}{5} \times \left(\frac{M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-Gly}))}}{44}\right) \times \left(\frac{4}{A_\text{b}}\right)$$
$$\times 104 + M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-BiBGE}))} \quad (6)$$

where A_m and A_b were the integral areas in ^{1}H NMR [Fig. 3(B)], and 104 was the molecular weight of St unit, and others were the same as before.

On the other hand, in the grafting copolymers, the main chain was wrapped by the PS chains, so the integration of the proton peak area of main

Table 1. Data of the Comb-Like Copolymers mPEO-b-[Poly(EO-co-Gly)-g-PS]

Entry[a]	Time (h)	mPEO-b-[Poly(EO-co-Gly)-g-PS]				Cleaved PS	
		$M_{n(\text{SEC})}$ (g/mol)	PDI[b]	$M_{n(\text{NMR})}$[c] (g/mol)	$M_{n(\text{cal.})}$[d] (g/mol)	$M_{n(\text{SEC})}$[b] (g/mol)	PDI[b]
mPEO-b-[Poly(EO-co-Gly)-g-PS1]	1.0	18,000	1.09	73,300	63,200	2,800	1.15
mPEO-b-[Poly(EO-co-Gly)-g-PS2]	2.0	23,000	1.10	93,000	73,100	3,300	1.14
mPEO-b-[Poly(EO-co-Gly)-g-PS3]	3.0	41,000	1.14	131,000	106,000	5,200	1.20

[a] The molar ratio of CuBr, bpy, and St to —Br groups was 1:1:100:1.
[b] Number-average molecular weight ($M_{n(\text{SEC})}$) and PDI were determined by SEC, calibrated against PS standards using THF as elution.
[c] $M_{n(\text{NMR})}$ were obtained from eq 6.
[d] $M_{n(\text{cal.})}$ were calculated by eq 7.

chain and part of the PS chain close to the main chain in ^{1}H NMR were not very accurate. Thus, the methine and methylene protons from the main chain showed a weak peak in the ^{1}H NMR spectrum due to the partial immobilization of the protons on the main chain, and this deviation for the measurement of molecular weight was inevitable for the ^{1}H NMR analysis of graft copolymers. To obtain the more reliable results, the PS side chains were cleaved from the mPEO-b-Poly-(EO-co-Gly) main chain. Figure 2(A) shows the SEC curve of cleaved PS1 and a monomodal peak with a narrow distribution (PDI = 1.15) was observed. Correspondingly, the number average molecular weight of mPEO-b-[Poly(EO-co-Gly)-g-PS] $M_{n(\text{cal.})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-PS])}}$ could also be calculated by eq 7 (Table 1).

$$M_{n(\text{cal.})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-PS])}}$$
$$= M_{n(\text{SEC})(\text{PS})} \times (N_{\text{EEGE}} + 1)$$
$$+ M_{n(\text{cal.})(m\text{PEO-}b\text{-Poly(EO-}co\text{-Gly))}} \quad (7)$$

Comparing the $M_{n(\text{cal.})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-PS])}}$ with $M_{n(\text{NMR})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-PS])}}$, the latter was slightly larger than the former, it may attribute to the wrapped protons on mPEO-b-Poly(EO-co-Gly) main chain.

Synthesis of mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)] by "Graft Onto" Strategy

Based on the ATNRC reaction, when a polymer chain containing TEMPO group was mixed with another halide-containing polymer in the presence of CuBr/PMDETA under heating, the terminal bromine group served as oxidant was reduced to bromine anion, whereas Cu$^+$ was oxidized to Cu^{2+} accordingly. Meanwhile, the formed second-

ary carbon radical was immediately captured by the TEMPO radical in another polymer chain, forming an alkoxyamine between the two polymers. In this reaction, CuBr was oxidized to CuBr$_2$, and the process is irreversible, which was quite different from the ATRP.

In this system, the TEMPO-PEO was prepared by ROP of EO using DPMK and HTEMPO as coinitiator, then it was mixed with mPEO-b-[Poly-(EO-co-Gly)-g-PS] in toluene and in the presence of CuBr/PMDETA at 90 °C (Scheme 2), the ATNRC reaction could be carried out smoothly. After complete removal of copper salts by neutral alumina column, the crude product mPEO-b-[Poly-(EO-co-Gly)-g-(PS-b-PEO)] was purified by ultrafiltration membrane using methanol as the
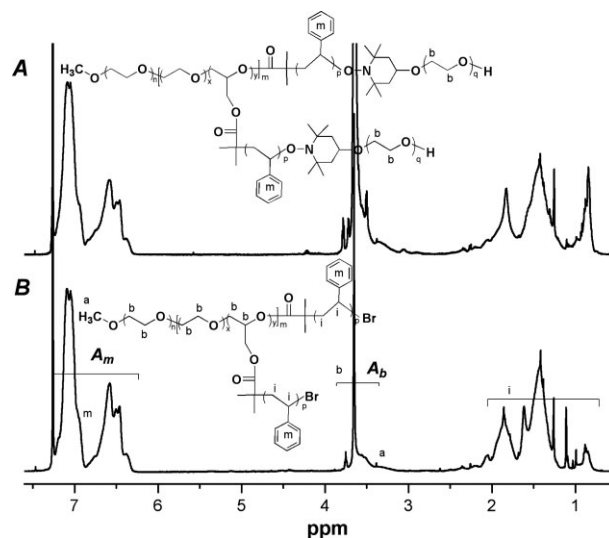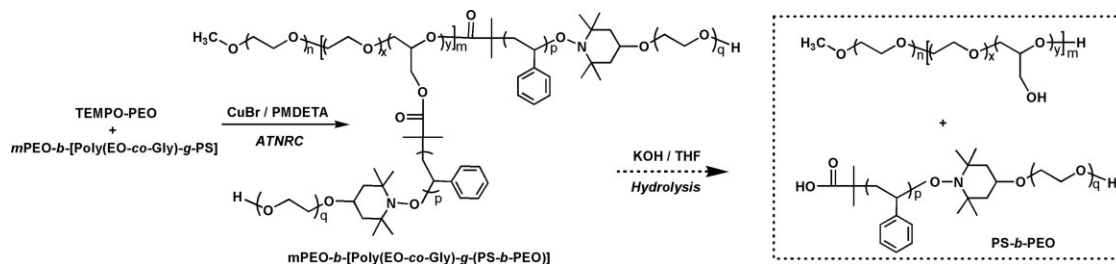

Figure 3. ^{1}H NMR spectrum of mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)] (A) and mPEO-b-[Poly(EO-co-Gly)-g-PS] (B).

Scheme 2. The synthesis procedure of comb-like block copolymers mPEO-b-[Poly-(EO-co-Gly)-g-(PS-b-PEO)] and their cleavage.

solvent, which was an efficient method to remove the unreacted TEMPO-PEO.

The SEC curve of mPEO-b-[Poly(EO-co-Gly)-g-(PS1-b-PEO)] was shown in Figure 2(C). Although it was a monomodal peak, but the molecular weight of the comb-like block copolymer was smaller than that of mPEO-b-[Poly(EO-co-Gly)-g-PS1] in Figure 2(D), which was unexpectedly and repeatedly observed. It might be attributed to the difference in the hydrodynamic volumes of the complicated grafting copolymer with linear PS standard. This phenomenon was also found by other researchers.[26,27]

Figure 3(A) showed the ^{1}H NMR spectrum of mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)], which was featured by two main regions. The resonances of the methylene groups on mPEO-b-Poly(EO-co-Gly) could be observed in 3.49–3.69 ppm, phenyl groups on PS occur in the region of 6.30–7.30 ppm. Compared with Figure 3(B), the signal at 3.49–3.69 ppm was increased obviously after ATNRC reaction, and it may attribute to the introduction of PEO segments of the grafted PS-b-PEO.

After the cleavage of PS-b-PEO block from grafting copolymer mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)], the SEC curve gave a monomodal peak with the low PDI [Fig. 2(B)]. According to the already known M_n of cleaved PS and TEMPO-PEO, the EF of ATNRC was achieved by analyzing the ^{1}H NMR of PS-b-PEO side chains using eq 8, and the corresponding molecular weight $M_{n(\text{cal.})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-(PS-}b\text{-PEO)]})}$ could be calculated according to eq 9:

$$\text{EF} = \frac{\left(\dfrac{A_r}{4}\right) \Big/ \left(\dfrac{M_{n(\text{NMR})(\text{TEMPO-PEO})}}{44}\right)}{\left(\dfrac{A_m}{5}\right) \Big/ \left(\dfrac{M_{n(\text{NMR})(\text{PS})}}{104}\right)} \times 100\% \quad (8)$$

$$M_{n(\text{cal.})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-(PS-}b\text{-PEO)]})}$$
$$= (N_{\text{EEGE}} + 1) \times \big[M_{n(\text{SEC})\text{PS}}$$
$$+ M_{n(\text{SEC})(\text{TEMPO-PEO})} \times \left(\text{EF}\right)\big] \quad (9)$$

where A_m and A_r were the integral areas in ^{1}H NMR [Fig. 3(A)]. $M_{n(\text{SEC})(\text{PS})}$ and $M_{n(\text{SEC})(\text{TEMPO-PEO})}$ were the M_n of PS and TEMPO-PEO obtained by SEC. Others were the same as before and all the data were listed in Table 2.

From Table 2, it was observed that, in the synthesis of comb-like block copolymers with complicated structure, the ATNRC reaction was efficient and valuable strategy with a high efficiency ($>90\%$).

Table 2. Data of Comb-Like Block Copolymers mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)]

| Entry | mPEO-b-[Poly(EO-co-Gly)-g-(PS-b-PEO)] | | | | Cleaved PS-b-PEO | |
	$M_{n(\text{SEC})}$[a] (g/mol)	PDI[a]	$M_{n(\text{cal.})}$[b] (g/mol)	EF[c]	$M_{n(\text{SEC})}$[a] (g/mol)	PDI[a]
mPEO-b-[Poly(EO-co-Gly)-g-(PS1-b-PEO)]	9,000	1.05	131,600	95%	4,900	1.15
mPEO-b-[Poly(EO-co-Gly)-g-(PS2-b-PEO)]	9,900	1.10	139,300	92%	6,400	1.09
mPEO-b-[Poly(EO-co-Gly)-g-(PS3-b-PEO)]	10,500	1.08	173,000	93%	7,200	1.17

[a] Number-average molecular weight ($M_{n(\text{SEC})}$) and PDI determined by SEC, calibrated against PS standards use THF as elution.
[b] The molecular weight $M_{n(\text{NMR})(m\text{PEO-}b\text{-[Poly(EO-}co\text{-Gly)-}g\text{-(PS-}b\text{-PEO)]})}$ was calculated by eq 9 according to ^{1}H NMR.
[c] The efficiency (EF) of ATNRC was calculated by eq 8 according to ^{1}H NMR.

CONCLUSIONS

The comb-like block copolymers with PS-*b*-PEO side chains and *m*PEO-*b*-Poly(EO-*co*-Gly) main chain were synthesized via sequential ROP, ATRP, and ATNRC reaction by "Graft from" and "Graft onto" strategies. The results showed that the efficiency of ATNRC in preparation of comb-like polymers was quite high.

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