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Synthesis of water-soluble statistical copolymers and terpolymers containing pendent oligo(ethylene glycol derivatives)

M. Vamvakaki, N.C. Billingham, S.P. Armes*

School of Chemistry, Physics and Environmental Science, University of Sussex, Falmer, Brighton BN1 9QJ, UK

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Abstract

A series of water-soluble pendent oligo(ethylene glycol)-based statistical copolymers and terpolymers were synthesised using group transfer polymerisation (GTP). More specifically, oligo(ethylene glycol) monomethyl ether monomethacrylate (OEGMA) macromonomers containing 6, 21 or 44 ethylene glycol units were copolymerised with either benzyl methacrylate (BzMA), 2-(dimethylamino)ethyl methacrylate (DMAEMA) or tetrahydropyranyl methacrylate (THPMA) to give statistical copolymers. The analogous terpolymers were obtained by copolymerising the oligo(ethylene glycol) monomethyl ether monomethacrylates with *n*-butyl methacrylate (*n*BuMA) and either BzMA or DMAEMA. Gel permeation chromatography was used to determine copolymer molecular weights and polydispersities, while proton NMR spectroscopy was used to assess their compositions. In all cases, the final copolymers were near-monodisperse (M_w/M_n's < 1.2) and good molecular weight control was achieved. The BzMA-containing copolymers were deprotected via catalytic hydrogenolysis to selectively remove the benzyl groups, giving polymers containing carboxylic acid groups. Similarly, the THPMA-containing polymers were deprotected by acidic hydrolysis to remove the tetrahydropyranyl groups, also resulting in acidic statistical polymers. Comparison of the degrees of deprotection achieved using the BzMA and THPMA protected monomers suggests that THP is the preferred protecting group since it is removed quantitatively regardless of the copolymer composition. In contrast, incomplete deprotection was obtained for the copolymers containing more than 67 mol% BzMA.

Keywords: Group transfer polymerisation; Macromonomers; Oligo(ethylene glycol) monomethyl ether monomethacrylate

1. Introduction

PEO is a common non-ionic synthetic polymer. Its non-toxicity and compatibility with a wide range of other substances have promoted its use in biomedical, cosmetic, household and industrial applications [1]. The micellisation of hydrophilic–hydrophobic block copolymers, with PEO as the water-soluble block and either polystyrene [2,3], poly(2-vinylpyridine) [4], poly(propylene oxide) (PPO) [5,6] or poly(butylene oxide) [7,8] as the hydrophobic block, has been extensively studied over the last decade. Particular interest has been paid to the complex aqueous solution properties of triblock PEO–block-PPO–block-PEO copolymers known as Pluronics or Synperonics [9–13]. Similar PEO-based amphiphilic block and graft copolymers with hydrophobic comonomers such as styrene and methyl methacrylate have been reported to be efficient emulsifiers [2,14] and stabilisers [15–18] in colloidal applications. Recently, a German group [19,20] reported the use of PEO-based ‘double-hydrophilic’ block copolymers as effective steric stabilisers for precipitating $CaCO_3$. In addition the aqueous micellisation behavior of water-soluble block copolymers comprising PEO and poly(*N*-isopropylacrylamide) (PNiPAAm) was investigated by Lee et al. [21]. The PEO chain length was shown to affect the LCST of these block copolymers. Moreover, PEO's with different molecular weights have been used in liquid chromatography modelling [22] and in the development of polymer electrolytes for batteries [23].

Recently, there has been considerable interest in the synthesis of amphiphilic graft copolymers composed of hydrophobic backbones and hydrophilic “hairs” obtained by copolymerisation of PEO derivatives with various comonomers [24]. The starting monomers are PEO macromonomers with either styryl [25] or methacrylate [26] end groups. Both homopolymers and copolymers of the latter macromonomer have been used as stabilisers [25], emulsifiers [27], and blood compatibilisers [28]. However, in all the examples cited previously the (co)polymers were prepared by conventional free-radical polymerisation and therefore

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* Corresponding author. Tel: + 44-1273-678650; fax: + 44-1273-677196.

E-mail address: s.p.armes@sussex.ac.uk (S.P. Armes)

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only limited control over their backbone structure and molecular weight distribution was achieved. So far, there have been few reports of the controlled polymerisation of PEO macromonomers. One example is the TEMPO-mediated copolymerisation of methacryloyl-terminated PEO macromonomer with styrene, reported by Wang and Huang [29]. In addition, Du Pont recently patented the GTP synthesis of methacrylic ABC triblock copolymers [30] containing triethylene glycol monoethyl ether monomethacrylate. These copolymers consisted of at least one hydrophilic and one hydrophobic block and incorporated either acidic or basic monomers. Such copolymers were claimed to be useful for pigment dispersion in aqueous media. Subsequently, copolymerisation of higher molecular weight oligo(ethylene glycol) monomethacrylate (OEGMA400) via GTP was reported and the application of these copolymers for pigment dispersion has been described [31].

GTP is a living polymerisation technique which involves a Michael-type addition using a silyl ketene acetal initiator [32]. It has been widely used for the synthesis of controlled structure (meth)acrylate (co)polymers of narrow molecular weight distribution at ambient temperature. These (co)polymers have found applications as stabilisers [15], dispersants [33] and in membrane preparation [34].

Functional groups which are susceptible to side-reactions in classical anionic polymerisation are more tolerant of GTP conditions. For example, allyl [35] and styryl [36] residues can be introduced into the polymer chain. These groups can then undergo further reactions to give more complex architectures. However, monomers containing labile protons (alcohols, acids) require protection prior to GTP. The synthesis of poly(methacrylic acid) (PMAA) has been reported using trimethylsilyl methacrylate, [37] *t*-butyl methacrylate, [38] tetrahydropyranyl methacrylate [39] and benzyl methacrylate [40] as the protected monomer. Hydrolysis, thermolysis or catalytic hydrogenolysis yields the target PMAA quantitatively.

In the present work, we report the synthesis of a series of novel oligo(ethylene glycol) monomethyl ether monomethacrylate-based comb copolymers and terpolymers containing either acidic or basic residues. Three oligo(ethylene glycol) monomethyl ether monomethacrylate (OEGMA) monomers of different molecular weights (MW = 350, 1,000 and 2,000) were used. Both benzyl and tetrahydropyranyl methacrylate were evaluated as protected monomers for methacrylic acid residues. Basic residues were obtained by direct copolymerisation with 2-(dimethylamino)ethyl methacrylate (DMAEMA). Terpolymers were obtained by statistical copolymerisation of OEGMA with *n*-butyl methacrylate (*n*BuMA) and either benzyl methacrylate (BzMA) or DMAEMA. In each case copolymer compositions and molecular weight distributions were assessed using ^{1}H NMR spectroscopy and gel permeation chromatography, respectively.

2. Experimental

2.1. Materials

The three OEGMAs were kindly donated by Inspec, UK ($M_w/M_n = 1.1$ as determined by GPC, while proton NMR gave ~ 6, 21 and 44 ethylene glycol units for OEGMA350, OEGMA1000 and OEGMA2000, respectively). The tetrahydropyranyl methacrylate (THPMA) monomer was prepared by the method of Armstrong [41]. All other monomers were obtained from Aldrich; inhibitors were removed from liquid monomers using basic alumina columns. The OEGMA's of molecular weights 1000 and 2000 were freeze-dried under vacuum, dissolved in a minimum amount of dry tetrahydrofuran (THF) under N_2 and any alcohol or acid impurities destroyed by stirring with bis(dimethylamino)methylsilane (ex. ABCR) for at least 2 h prior to use [42]. All other monomers were dried by stirring over calcium hydride and stored at − 20°C until required. The OEGMA of molecular weight 350 and BzMA were each filtered into a graduated Schlenk flask and stirred with bis(dimethylamino)methylsilane for at least 2 h prior to use. All other monomers were freshly distilled prior to use. The 1-methoxy-1-trimethylsiloxy-2-methyl-1-propene (MTS) initiator was obtained from Aldrich, distilled and stored at − 5°C prior to use. THF (Fisons) was dried over sodium wire for 3 days and then refluxed over potassium for a further 3 days. The dried solvent was stored over 4 Å molecular sieves prior to use. The *n*-tetrabutylammonium bibenzoate (TBABB) catalyst was prepared by the method of Dicker et al. [43].

2.2. Copolymer syntheses

Polymerisations were performed under dry nitrogen using standard Schlenk techniques. All glassware was oven-dried overnight at 175°C before use. Assembled glassware was then flamed out under vacuum to eliminate surface moisture. In a typical synthesis, TBBAB (ca. 20 mg, 2 mol% based on initiator) and MTS (0.25 mL) were added to THF (120 mL). The freshly distilled monomers, (OEGMA350, 8.75 mL and *n*BuMA, 8.50 mL premixed with DMAEMA, 2.00 mL) were added separately dropwise via two double-tipped needles at an approximate rate of 1 mL per min. The reaction exotherm (~10°C) was measured using a contact thermocouple. The reaction mixture was left stirring at room temperature for 2.5 h before being quenched by the addition of methanol (2 mL). The terpolymer was recovered by removing the solvent using a rotary evaporator before drying in a vacuum oven for 3 days at room temperature. This procedure resulted in a statistical terpolymer containing 29–58–13 mol% OEGMA350–*n*BuMA–DMAEMA, with an M_n of *ca.* 16,900 g mol^{-1} by GPC (vs. PMMA standards). Copolymers of different compositions were prepared by varying the comonomer ratios at a fixed initiator concentration. Copolymer molecular weights were varied by controlling the comonomer/initiator ratio.

2.3. Catalytic hydrogenolysis

Catalytic hydrogenolyses of BzMA-based copolymers were performed in a solvent mixture such that the copolymer remained soluble throughout the derivatisation. Thus, copolymer (10 g) was dissolved in 220 mL of 10/1 ethyl acetate/methanol and 2.7 g of 10% Pd/C catalyst was added to this solution under nitrogen. The reaction solution was stirred under hydrogen (1 atm.) at room temperature for at least 10 days. Finally, the catalyst was filtered off and the copolymer was recovered using a rotary evaporator, prior to drying in vacuo for 2 days at room temperature.

2.4. Acid hydrolysis

The THPMA-containing copolymers were deprotected by acid hydrolysis in 0.1 M HCl in THF at room temperature in which both the precursor and the final acidic copolymer were soluble. In a typical hydrolysis the copolymer (40 g) was dissolved in 1 L THF and 60 mL of 2 M HCl was added to obtain a solution of 0.1 M HCl in THF. The reaction was stirred for 2–3 days before neutralising the excess HCl with KOH and filtering off the THF-insoluble KCl. Excess solvent was removed using a rotary evaporator and the copolymer was precipitated in *n*-hexane. Finally, the copolymer was freeze-dried from water.

2.5. Gel permeation chromatography

Molecular weights and molecular weight distributions of all the copolymers were determined using both non-aqueous and aqueous gel permeation chromatography (GPC). The non-aqueous GPC set-up comprised a Perkin Elmer LC pump, an RI detector, and a PLgel 3 m Mixed ’E’ column (Polymer Labs). Calibration was carried out using a series of poly(methyl methacrylate) (PMMA) standards (Polymer Labs), with M_n’s ranging from 625 to 29,400. The eluent was HPLC grade THF at a flow rate of 1 mL min^{-1}.

Aqueous GPC was used to assess molecular weights and molecular weight distributions of selected deprotected water-soluble copolymers. This set-up comprised a Polymer Labs HPLC pump, an RI detector, and a PL aquagel-OH 40 column (Polymer Labs). Calibration was carried out using PEO standards (Polymer Labs), with M_n’s ranging from 620 to 22,800. The eluent was a 0.25 M $NaNO_3$/0.01 M NaH_2PO_4 solution in doubly-distilled water (pH 7) at a flow rate of 1 mL min^{-1}.

2.6. FTIR spectroscopy

All FTIR spectra were recorded using a Nicolet Magna 550 Series II instrument with an ATR accessory. Typically 64 scans were collected for each spectrum at a resolution of 4 cm^{-1}.

2.7. Nuclear magnetic resonance spectroscopy

All ^{1}H NMR spectra were recorded using a Bruker 250 MHz instrument, using either CD_2Cl_2 or $CDCl_3$ solvents for the BzMA-containing copolymers and the DMAEMA- and THPMA-containing copolymers, respectively. The degrees of deprotection of the OEGMA–MAA copolymers were assessed from proton NMR spectra recorded in either d_6-DMSO or d_7-DMF.

3. Results and discussion

A series of OEGMA-based statistical copolymers with either BzMA or DMAEMA was synthesised, as well as their corresponding terpolymers with *n*BuMA (see Table 1, Table 2, Table 3). A range of OEGMA macromonomers was used containing an average of 6, 21 and 44 ethylene glycol units (OEGMA350, OEGMA1000 and OEGMA2000, respectively). Copolymerisation of OEGMA with DMAEMA (and *n*BuMA) yielded copolymers containing tertiary amine groups directly. The BzMA-containing copolymers were deprotected by catalytic hydrogenolysis to selectively remove the benzyl groups, giving statistical copolymers and terpolymers containing carboxylic acid groups (see Fig. 1).

A second series of OEGMA350-based statistical copolymers with THPMA were synthesised (see Table 4). In agreement with observations reported in an earlier study by Lowe et al. [44,45] some problems were encountered in the homopolymerisation of THPMA. Only a low yield (60%) and a homopolymer of broad molecular weight distribution was obtained. However, high conversions and copolymers of narrow polydispersities were obtained when THPMA was copolymerised with OEGMA350 to give OEGMA350–stat-THPMA copolymers. The comonomer composition was varied while the copolymer molecular weight was kept constant, resulting in copolymers with OEGMA contents

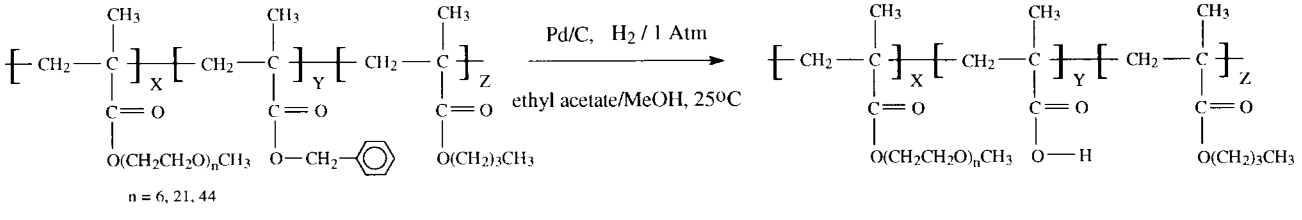


Fig. 1. Reaction scheme for the catalytic hydrogenolysis of BzMA-based copolymers.

Table 1
Copolymer compositions, number-average molecular weights and polydispersities of OEGMA350-based statistical copolymers

(Co)polymer	Theor. (Co)polymer composition (mol%)	(Co)polymer composition by ^{1}H NMR (mol%)	Theor. M_n of stat.(co)polymer[a]	M_n of stat. (co)polymer[a]	M_w/M_n[a]	Conversion[a](%)
OEGMA350	100	100	6,300	9,900	1.12	> 99
OEGMA350	100	100	7,100	11,800	1.11	> 99
OEGMA350–stat-BzMA	33–67	33–67	11,600	12,800	1.16	> 99
OEGMA350–stat-DMAEMA	31–69	31–69	20,800	24,300	1.12	> 99
OEGMA350–stat-*n*BuMA–stat-BzMA	30–58–12	31–58–11	14,100	16,400	1.08	> 99
OEGMA350–stat-*n*BuMA–stat-DMAEMA	29–58–13	29–58–13	15,400	16,900	1.09	> 99

[a] As determined by GPC (PMMA standards, THF, 1 mL min^{-1}, RI detector).

Table 2
Copolymer compositions, number-average molecular weights and polydispersities of OEGMA1000-based statistical copolymers

(Co)polymer	Theor. (Co)polymer composition (mol%)	(Co)polymer composition by ^{1}H NMR (mol %)	Theor. M_n of stat. (co)polymer	M_n of stat. (co)polymer[a]	M_w/M_n[a]	Conversion[a] (%)
OEGMA1000	100	100	10,200	16,500	1.07	92
OEGMA1000–stat-BzMA	15–85	15–85	14,100	18,000	1.17	99
OEGMA1000–stat-DMAEMA	14–86	13–87	13,900	13,700	1.14	95
OEGMA1000–stat-*n*BuMA–stat-BzMA	13–72–15	12–73–15	15,400	22,100	1.08	99
OEGMA1000–stat-*n*BuMA–stat-DMAEMA	12–72–16	12–72–16	15,400	22,800	1.08	98

[a] As determined by GPC (PMMA standards, THF, 1 mL min^{-1}, RI detector).

Table 3
Copolymer compositions, number-average molecular weights and polydispersities of OEGMA2000-based statistical copolymers

(Co)polymer	Theor. (Co)polymer composition (mol%)	(Co)polymer composition by ^{1}H NMR (mol %)	Theor. M_n of stat.(co)polymer	M_n of stat.(co)polymer[a]	M_w/M_n[a]	Conversion[a] (%)
OEGMA2000	100	100	10,200	15,400	1.08	90[b]
OEGMA2000 (@ 0°C)	100	100	9,600	20,600	1.11	84
OEGMA2000 (@ 0°C, 10% CH_2Cl_2)	100	100	9,700	15,500	1.09	74
OEGMA2000 (RT, $TASHF_2$ catalyst)	100	100	9,700	20,200	1.19	85
OEGMA2000–stat-BzMA	10–90	11–89	10,900	13,000	1.11	97
OEGMA2000–stat-BzMA	8–92	8–92	16,900	24,600	1.13	96
OEGMA2000–stat-DMAEMA	10–90	11–89	11,400	16,400	1.08	97
OEGMA2000–stat-DMAEMA	7–93	7–93	16,700	21,000	1.11	95
OEGMA2000–stat-*n*BuMA–stat-BzMA	7–77–16	7–77–16	15,400	18,200	1.13	95
OEGMA2000–stat-*n*BuMA–stat-DMAEMA	7–76–17	7–76–17	15,400	22,800	1.11	95

[a] As determined by GPC (PMMA standards, THF, 1 mL min^{-1}, RI detector).
[b] After dialysis against water to remove unreacted macromonomer.

Table 4
Copolymer compositions, number-average molecular weights and polydispersities of OEGMA350-THPMA statistical copolymers

(Co)polymer	Theor. (Co)polymer composition (mol%)	(Co)polymer composition by ^{1}H NMR (mol %)	Theor. M_n of stat. (co)polymer	M_n of stat. (co)polymer[a]	M_w/M_n[a]	Conversion[a] (%)
THPMA	100	—	8,100	12,600	1.40	60
OEGMA350–stat-THPMA	10–90	13–87	10,000	8,000	1.08	80
OEGMA350–stat-THPMA	20–80	20–80	10,200	13,000	1.12	97
OEGMA350–stat-THPMA	30–70	31–69	9,900	13,200	1.08	99
OEGMA350–stat-THPMA	40–60	40–60	9,900	12,100	1.09	100
OEGMA350–stat-THPMA	50–50	52–48	10,100	8,300	1.13	95
OEGMA350–stat-THPMA	60–40	61–39	10,100	12,700	1.07	99
OEGMA350–stat-THPMA	70–30	71–29	10,300	8,600	1.09	99
OEGMA350–stat-THPMA	80–20	81–19	10,200	12,800	1.09	100
OEGMA350–stat-THPMA	90–10	90–10	10,100	8,300	1.10	100

[a] As determined by GPC (PMMA standards, THF, 1 mL min^{-1}, RI detector).

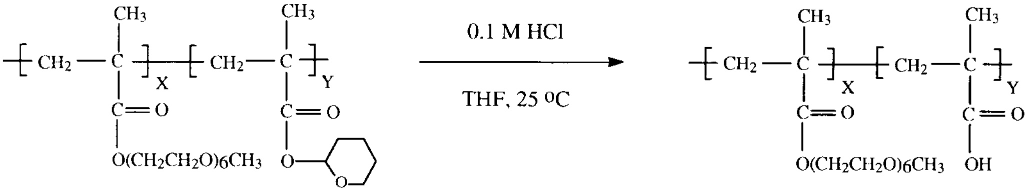


Fig. 2. Reaction scheme for the acidic hydrolysis of THPMA-based copolymers.

varing from 10% to 90%. The copolymers were then deprotected by acidic hydrolysis to selectively remove the tetrahydropyranyl groups giving OEGMA–stat-MAA copolymers similar to those obtained via deprotection of the BzMA residues (see Fig. 2).

Statistical copolymers were prepared by copolymerising OEGMA macromonomers with either BzMA, DMAEMA or THPMA. The OEGMA monomer was added as a solution in dry THF. In order to allow the less reactive OEGMA to copolymerise readily and thus obtain genuine statistical architectures the two monomers were each drip-fed into the reaction vessel simultaneously but the OEGMA was added at a higher rate than the comonomer. Terpolymers were prepared by simply adding the *n*BuMA monomer premixed with either DMAEMA or BzMA, assuming a similar reactivity ratio for the two pre-mixed comonomers. Comonomer compositions were varied widely (10–90 mol% OEGMA) but the overall copolymer molecular weight was maintained at ca. 10 000–20 000 g mol^{-1} (see Tables 1–4). Most of the copolymers were easily isolated by removing excess THF using a rotary evaporator and then drying the resulting viscous solution in a vacuum oven at room temperature. Copolymers of high OEGMA content were further purified by precipitation in *n*-hexane, before drying in the vacuum oven. Monomer conversion was estimated by both GPC (by comparing the copolymer and comonomer signals) and ^{1}H NMR (by comparing peak integrals assigned to the polymer and comonomers). Excellent yields were obtained in most cases, except when homopolymerising the higher molecular weight OEGMA macromonomers (MW 1000 and 2000). The reaction yields for these homopolymerisations, even under more stringent conditions (TASHF$_2$ catalyst, 0°C), were lower than those normally expected from a GTP reaction. This is most likely because of the bulkiness and hence reduced reactivity of these macromonomers. It is well known that macromonomers do not readily homopolymerise to full conversion [46]. Nevertheless, these OEGMA homopolymers can be isolated in reasonably good yields via dialysis against water to remove the unreacted macromonomer (see Table 3). Essentially quantitative conversions were obtained by copolymerisation of the OEGMA macromonomers with low molecular weight comonomers such as DMAEMA or BzMA. Some problems were also encountered when synthesising THPMA-rich copolymers. THPMA did not homopolymerise to full conversion and a reduced yield was also observed for the 10–90 OEGMA350–stat-THPMA copolymer, but conversions were quantitative in all other cases. Copolymer molecular weights and molecular weight distributions were determined by GPC (see Fig. 3) and are summarised in

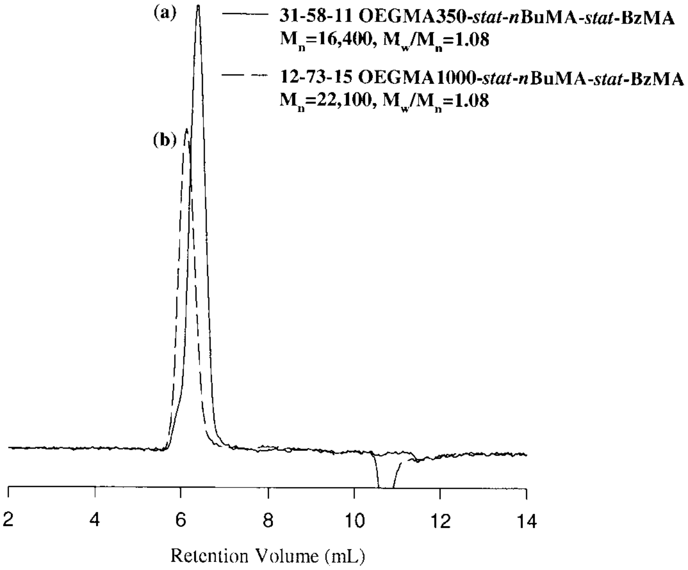


Fig. 3. Typical gel permeation chromatograms for (a) a 31–58–11 OEGMA350–stat-*n*BuMA–stat-BzMA and (b) a 12–73–15 OEGMA1000–stat-*n*BuMA–stat–BzMA terpolymer calibrated with poly(methyl methacrylate) standards.

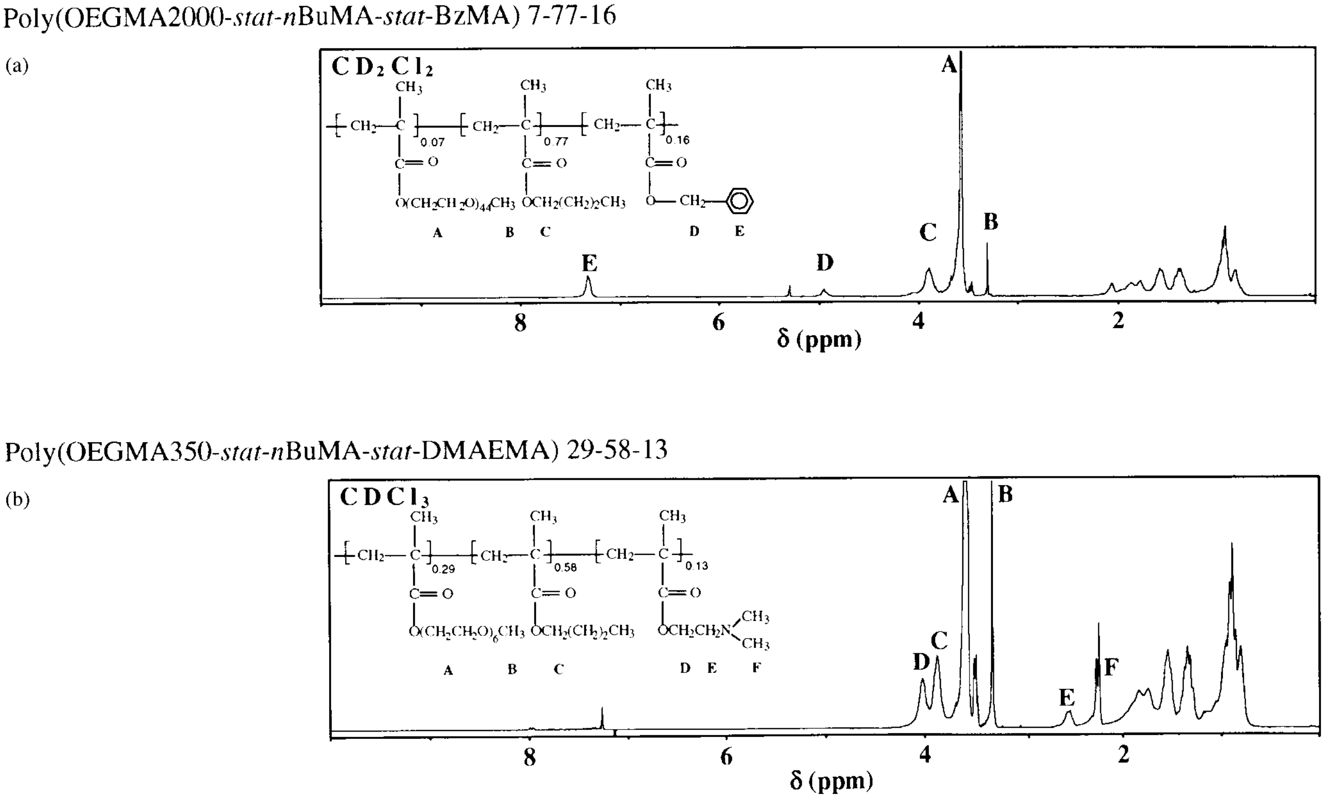


Fig. 4. Typical ^{1}H NMR spectra of (a) a 7–77–16 OEGMA2000–stat-*n*BuMA–stat-BzMA and (b) a 29–58–13 OEGMA350–stat-*n*BuMA–stat-DMAEMA terpolymer.

Tables 1–4. In general, good agreement between the theoretical and GPC molecular weights was observed, particularly given the likely differences in hydrodynamic volumes between the PMMA calibration standards and the copolymers synthesised in this work. The polydispersities of all copolymers were low ($M_w/M_n < 1.2$). Relative copolymer compositions were determined using ^{1}H NMR spectroscopy (see Fig. 4) by comparing selected peak integrals which were characteristic of the different comonomers. For example, the peak integral of the $-OCH_3$ protons in the OEGMA residues at $\delta 3.2–3.4$ was compared to that of the aromatic protons at $\delta 7.2–7.4$ for BzMA-containing copolymers (or to that of the dimethylamino protons at $\delta 2.2–2.4$ for the DMAEMA-containing copolymers, or to that of the acetal hydrogen of the THPMA ring at $\delta 5.8–5.9$ for the THPMA-containing copolymers). In general, the copolymer compositions were in good agreement with the expected values (see Tables 1–4).

BzMA-based copolymers and terpolymers were deprotected by catalytic hydrogenolysis (see Table 5). Debenzylation was indicated by FTIR spectroscopy. Before deprotection the polymer shows a sharp stretching vibration of the ester carbonyl bond at 1725 cm^{-1}. After deprotection the appearance of a new peak at 1700 cm^{-1} indicative of carboxylic acid groups together with the characteristic –OH band at 3450 cm^{-1} was consistent with successful deprotection. Further, the disappearance of the two very strong peaks at 749 and 698 cm^{-1} (assigned to the aromatic C–H out of plane bending vibration; this peak is characteristic of a mono-substituted aromatic ring [47]) in the IR spectrum of the deprotected BzMA-containing copolymer indicated the complete debenzylation of copolymers containing less than 67 mol% BzMA. Debenzylation was also indicated by the disappearance (or reduction) of the signals arising from the aromatic and benzylic protons in the proton NMR spectra of the precursor copolymers (see Fig. 5). The actual degree of debenzylation was determined by comparing the peak integral of the un-ionised carboxylic acid proton ($\sim \delta$ 12.5 in d_6-DMSO or d_7-DMF) of the deprotected copolymer to that of the $-COOCH_2-$ protons of the PEGMA residues (δ 4.0–4.2). Our observations are in agreement to those reported earlier by Mykytiuk et al. [40] and Rannard et al. [38], who achieved quantitative debenzylation of BzMA homopolymers and BzMA–MMA block copolymers, respectively. In order to verify that debenzylation had not resulted in any unwanted side-reactions, Mykytiuk et al. [40] remethylated a PMAA homopolymer using diazomethane to obtain PMMA, which was then analysed by GPC (THF eluent). This confirmed that the narrow molecular weight distribution of the poly(BzMA) precursor was retained in the final PMAA, as expected. Since the same mild conditions were used for debenzylation in the present study, no side-reactions, such as chain scission or cross-linking, were anticipated. However, in the present work

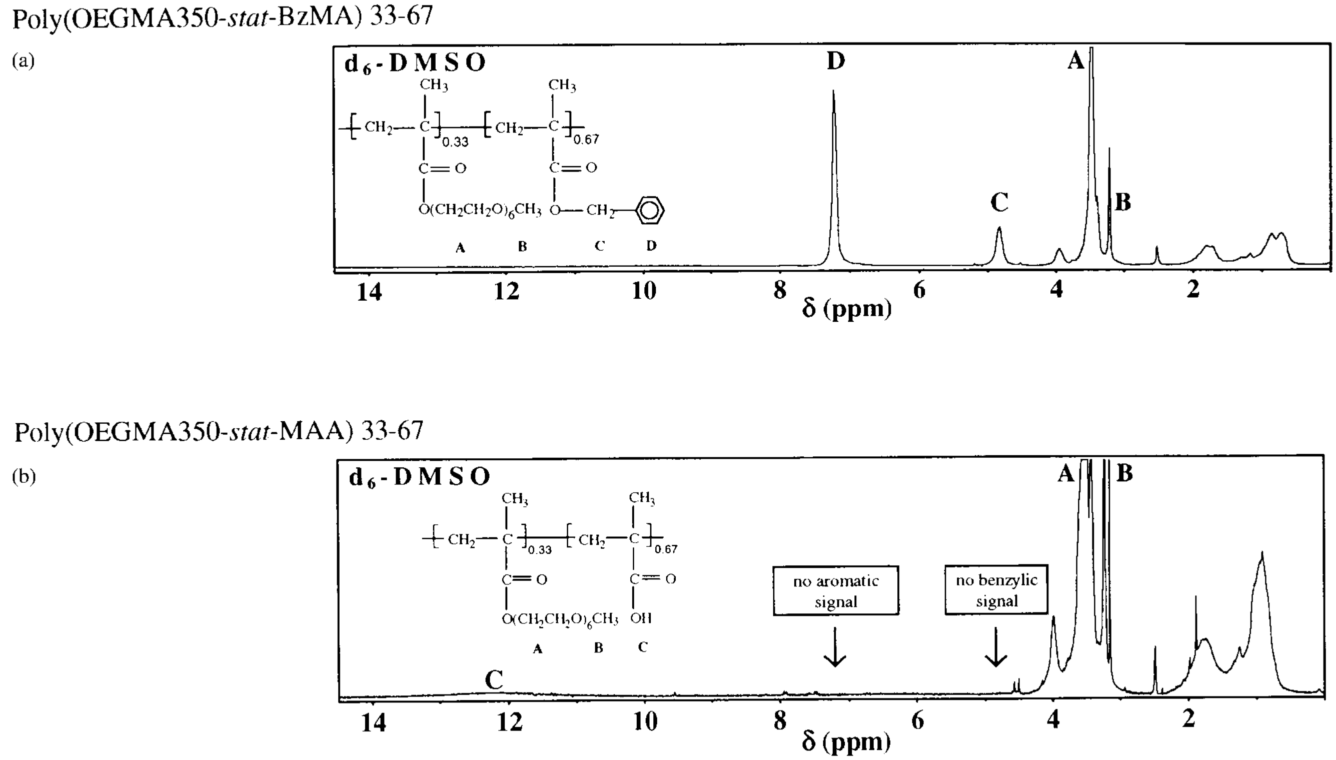


Fig. 5. Typical ^{1}H NMR spectra of (a) a 33–67 OEGMA350–stat-BzMA copolymer and (b) the final debenzylated 33–67 OEGMA350–stat-MAA copolymer obtained after catalytic hydrogenolysis.

quantitative debenzylation was only achieved for the copolymers and terpolymers which contained less than 67 mol% BzMA. At higher BzMA contents deprotection was substantially incomplete (see Table 5). Moreover, in all cases the deprotected copolymers suffered from significant catalyst contamination, even after filtration through a 0.2 μm filter. These observations are in excellent agreement with those reported earlier by Forder et al. [48] for tri(ethylene glycol) vinyl ether-based copolymers. It was suggested that the tri(ethylene glycol) residues led to strong adsorption onto the precious metal catalyst particles, causing discoloration of the deprotected acidic copolymers. Further, insufficient

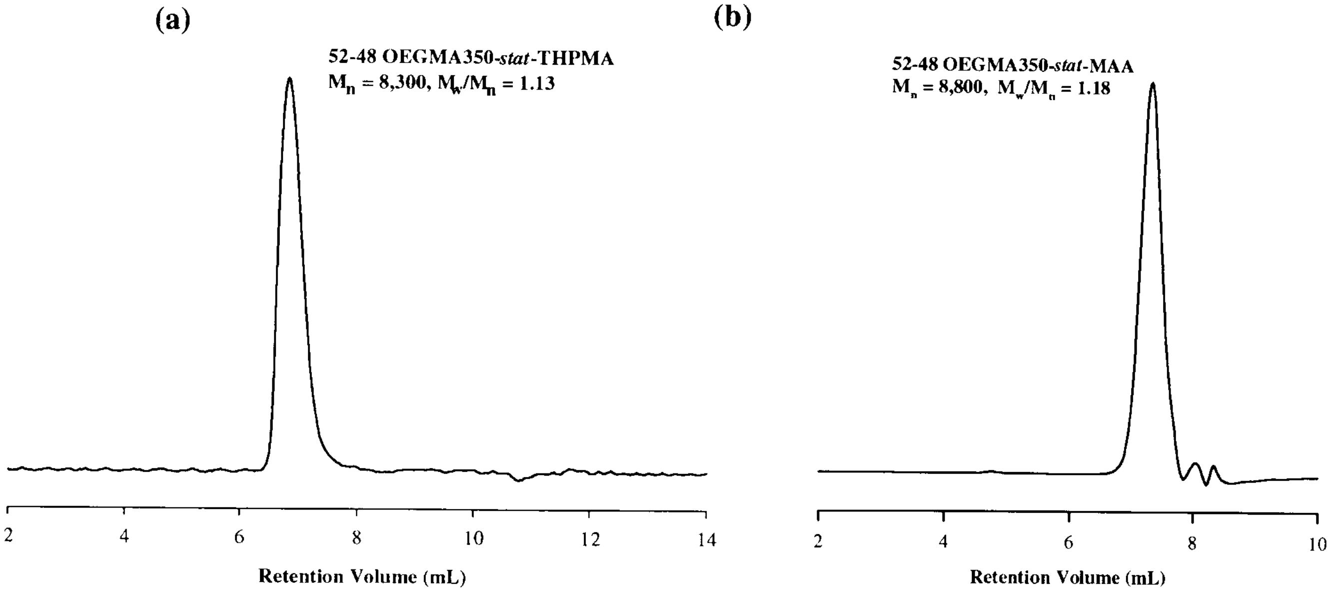


Fig. 6. Typical gel permeation chromatograms for (a) a 52–48 OEGMA350–stat-THPMA copolymer calibrated with poly(methyl methacrylate) standards in THF eluent and (b) the corresponding deprotected 52–48 OEGMA350–stat-MAA copolymer calibrated with poly(ethylene oxide) standards in aqueous eluent.

Table 5
Copolymer compositions of BzMA-based copolymers and their degrees of debenzylation after catalytic hydrogenolysis

Copolymer	Copolymer composition (mol%)	% Deprotection by ^{1}H NMR	M_n before deprotection	Calculated M_n after Deprotection	Reaction yield (%)[a]
OEGMA350–stat-BzMA	33–67	100	12,800	9,500	71
OEGMA1000–stat-BzMA	15–85	54	18,000	11,200	69
OEGMA2000–stat-BzMA	8–92	56	24,600	13,900	59
OEGMA350–stat-*n*BuMA–stat-BzMA	31–58–11	100	16,400	15,600	94
OEGMA1000–stat-*n*BuMA–stat-BzMA	12–73–15	100	22,100	20,900	94
OEGMA2000–stat-*n*BuMA–stat-BzMA	7–77–16	100	18,200	17,300	92

[a] Some loss of copolymer during filtration work-up.

Table 6
Copolymer compositions of THPMA-based copolymers and their degrees of deprotection after acid hydrolysis

Copolymer[a]	Copolymer composition (mol %)	M_n before deprotection[b]	M_n after deprotection[c]	M_w/M_n[b]	M_w/M_n[c]
OEGMA350–stat-MAA	13–87	8,000	7,700	1.08	1.07
OEGMA350–stat-MAA	20–80	13,000	7,400	1.12	1.11
OEGMA350–stat-MAA	31–69	13,200	8,600	1.08	1.06
OEGMA350–stat-MAA	40–60	12,100	9,200	1.09	1.05
OEGMA350–stat-MAA	52–48	8,300	8,800	1.13	1.18
OEGMA350–stat-MAA	61–39	12,700	9,100	1.07	1.06
OEGMA350–stat-MAA	72–28	11,500	8,500	1.09	1.18
OEGMA350–stat-MAA	81–19	12,800	8,200	1.09	1.18
OEGMA350–stat-MAA	90–10	8,300	9,000	1.10	1.20

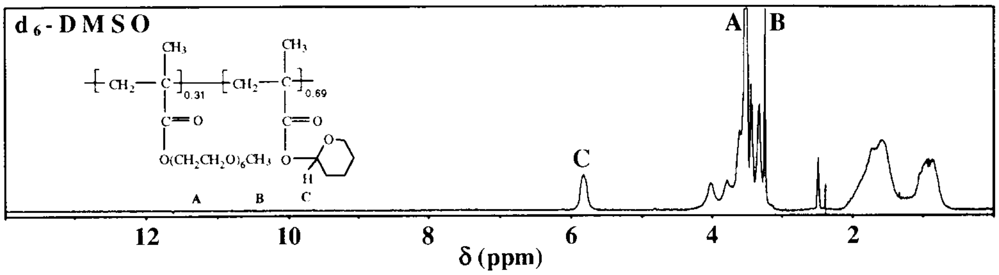
[a] Deprotection as determined by ^{1}H NMR was 100% in all cases.

[b] As determined by GPC (PMMA standards, THF, 1 mL min^{-1}, RI detector).

[c] As determined by aqueous GPC (PEO standards, 0.25 M $NaNO_3$/0.01 M NaH_2PO_4, 1 mL min^{-1}, RI detector).

Poly(OEGMA350-*stat*-THPMA) 31-69

(a)



Poly(OEGMA350-*stat*-MAA) 31-69

(b)

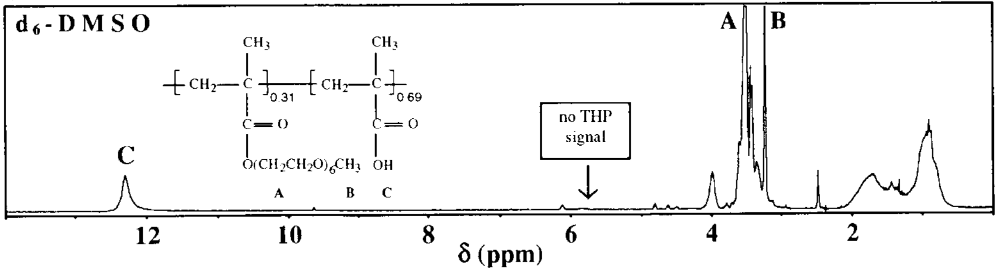


Fig. 7. Typical ^{1}H NMR spectra of (a) a 31–69 OEGMA350–stat-THPMA precursor copolymer and (b) the final deprotected 31–69 OEGMA350–stat-MAA copolymer obtained after acid hydrolysis.

catalyst surface resulting from copolymer adsorption probably accounts for the observed incomplete deprotection. Since similar ethylene glycol-based copolymers were examined in this study, both incomplete deprotection and copolymer discoloration were anticipated. Because of these problems an alternative protected monomer for the methacrylic acid residues was sought. In view of the successful synthesis of zwitterionic block copolymers reported by Lowe et al. [45] we evaluated THPMA as an alternative protected monomer for MAA residues.

MAA-containing copolymers free of catalyst contamination were obtained by the acidic hydrolysis of the OEGMA350–stat-THPMA precursor copolymers in acidified THF (see Table 6). Deprotection of a 10-90 OEGMA350–stat-THPMA copolymer was initially attempted in 0.1 M HCl but no reaction occurred as judged by proton NMR spectroscopy, probably because of the insolubility of the precursor copolymer. Therefore 0.1 M HCl in THF was used in all subsequent experiments in order to ensure that the copolymer remained soluble throughout the reaction. Aqueous GPC was used to confirm that the narrow molecular weight distributions of the precursors were retained in the deprotected acidic copolymers (see Fig. 6). The copolymer molecular weights and polydispersities were essentially unchanged after deprotection, suggesting that no significant side-reactions, such as chain scission or cross-linking, occurred under the mild conditions used for the deprotection. Qualitative evidence for deprotection was obtained using FTIR spectroscopy: the appearance of a new peak at ∽ 1700 cm^{-1} in the IR spectrum of the deprotected copolymer was assigned to the carbonyl stretch of the methacrylic acid residues. Degrees of deprotection (see Table 6) were determined using ^{1}H NMR spectroscopy (see Fig. 7). Quantitative deprotection was usually indicated by the complete disappearance of the signal due to the acetal hydrogen of the THPMA ring (at approximately δ5.8 in either d_6-DMSO or d_7-DMF) in the proton NMR spectra of the precursor copolymers. To determine the actual degree of deprotection, the peak integral of the un-ionised carboxylic acid proton signal (~ δ 12.5 in d_6-DMSO or d_7-DMF) of the deprotected copolymer (where applicable) was compared to that of the $-COOCH_2-$ protons signal of the OEGMA residues (δ 4.0–4.2) (see Fig. 7). Unlike the BzMA-based copolymers, quantitative deprotection was achieved for all the copolymers, regardless of their THPMA contents.

4. Conclusions

A series of well-defined, near-monodisperse water-soluble statistical copolymers based on OEGMA's has been synthesised in high yield using GTP. Good control over molecular weight was achieved. Polymerisation of OEGMA with DMAEMA gave directly copolymers and terpolymers containing tertiary amine residues. The OEGMA–BzMA copolymers were selectively deprotected by catalytic hydrogenolysis to obtain the corresponding OEGMA–MAA copolymers. Complete deprotection was only achieved for copolymers that contained less than 67 mol% BzMA as verified by proton NMR spectroscopy. Copolymer adsorption onto the heterogeneous precious metal catalyst leads to incomplete debenzylation for higher BzMA contents and also results in significant discoloration of the deprotected acidic copolymers. However, the THPMA-containing copolymers can be easily and fully deprotected by acidic hydrolysis regardless of their THPMA contents. Aqueous GPC confirmed that the narrow molecular weight distributions of the precursor copolymers were retained in these latter OEGMA–MAA copolymers. Hence, THPMA is the preferred protected monomer for the synthesis of OEGMA-based copolymers via GTP, particularly for high acid contents.

In summary, facile synthetic routes have been developed for the preparation of well-defined, low molecular weight OEGMA-based statistical copolymers and terpolymers. Applications of these hydrophilic copolymers are currently being explored.

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References

[1] Mark HF, Gaylord NG, Bikales NM, editors. Encyclopedia of polymer science and technology, vol. 6. New York: Interscience, 1964.
[2] Barker MC, Vincent B. Colloids Surf 1984;8:297.
[3] Yu K, Eisenberg A. Macromolecules 1996;29:6359.
[4] Martin TJ, Procházka K, Munk P, Webber SE. Macromolecules 1996;29:6071.
[5] Ding J, Attwood D, Price C, Booth C. Eur Polym J 1991;27(9):901.
[6] Deng Y, Yu G-E, Price C, Booth C. J Chem Soc Faraday Trans 1992;88(10):1441.
[7] Yang Z, Pickard S, Deng NJ, Barlow RJ, Attwood D, Booth C. Macromolecules 1994;27(9):2371.
[8] Yu GE, Yang YW, Yang Z, Attwood D, Booth C, Nace VM. Langmuir 1996;12(14):3404.
[9] Alexandridis P, Holzwarth JF, Hatton TA. Macromolecules 1994;27:2414.
[10] Michels B, Waton G. Zana R. Langmuir 1997;13:3111.
[11] Linse P, Malmsten M. Macromolecules 1992;25:5434.
[12] Linse P. Macromolecules 1993;26:4437.
[13] Mortensen K, Brown W. Macromolecules 1993;26:4128.
[14] Berlinova IV, Amzil A, Vladimirov NG. J Polym Sci Part A: Polym Chem 1995;33:1751.
[15] Winzor CL, Mrázek Z, Winnik MA, Croucher MD, Riess G. Eur Polym J 1994;30(1):121.
[16] Wu WWL, Piirma I. Polym Bull 1993;31:531.
[17] Liang W, Bognolo G, Tadros ThF. Langmuir 1995;11:2899.
[18] Bourgeat-Lami E, Guyot A. Polym Bull 1995;35:691.
[19] Colfen H, Antonietti M. Langmuir 1998;14(3):582.
[20] Sedlak M, Antonietti M, Colfen H. Macromol Chem Phys 1998;199:247.
[21] Lee KK, Jung JC, Jhon M. S Polym Bull 1998;40:455.
[22] Sassi A, Blanch HW, Prausnitz JM. J Appl Polym Sci 1996;59:1337.
[23] Cruickshank J, Hubbard HVStA, Boden N, Ward IM. Polymer 1995;36:3779.
[24] Bo G, Wesslén B, Wesslén KB. J Polym Sci Part A: Polym Chem 1992;30(9):1799.
[25] Chao D, Itsuno S, Ito K. Polym J 1991;23(9):1045.
[26] Gramain P, Frère Y. Polym Commun 1986;27:16.
[27] Marthur AM, Drescher B, Scranton AB, Klier J. Nature 1998;392(6674):367.
[28] Qui YX, Klee D, Plüster W, Severich B, Höcker H. J Appl Polym Sci 1996;61:2373.
[29] Wang Y, Huang J. Macromolecules 1998;31(13):4057.
[30] Dicker IB, Hertler WR, Ma S-H. US Pat. 5,219,945, 1993.
[31] Ma S-H, Dicker IB, Hertler WR. Europ. Pat. 0 556 649 A1, 1993.
[32] Sogah DY, Hertler WR, Webster OW, Cohen GM. Macromolecules 1988;20:1473.
[33] Al-Lami HS, Billingham NC, Calvert PD. Chem Mater 1992;4:1200.
[34] Rannard SP. DPhil Thesis. University of Sussex, 1993.
[35] Webster OW. US Pat. 4,417,034, 1983.
[36] Pugh C, Percec V. Polym Bull 1985;14:109.
[37] Al-Lami HS. DPhil Thesis. University of Sussex, 1989.
[38] Rannard SP, Billingham NC, Armes SP, Mykytiuk J. Eur Polym J 1993;29(2–3):407.
[39] Patrickios CS, Hertler WR, Abbott NL, Hatton TA. Macromolecules 1994;27:930.
[40] Mykytiuk J, Armes SP, Billingham NC. Polym Bull 1992;29:139.
[41] Armstrong JR. Canadian Pat. 672,947, 1963.
[42] Citron JD. US Pat. 4,771,116, 1988.
[43] Dicker IB, Farnham WB, Hertler WR, Laganis ED, Sogah DY, Del Pesco TW, Fitzgerald PH. US Pat. 4,588,795, 1986.
[44] Lowe AB. DPhil Thesis. University of Sussex, 1997.
[45] Lowe AB, Billingham NC, Armes SP. Chem Commun 1997;1035.
[46] Wintermantel M, Fischer K, Gerle M, Ries R, Schmidt M, Kajiwara K, Urakawa H, Wataoka I. Angew Chem Int Ed Engl 1995;34(13–14):1472.
[47] Morrison RT, Boyd RN. Organic chemistry. Boston, MA: Allyn and Bacon, 1976.
[48] Forder C, Patrickios CS, Armes SP, Billingham NC. Macromolecules 1997;30:5758.