Controlled polymerization of 2,3,5,6-tetrafluorophenyl methacrylate

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Abstract

Well-defined homopolymer of 2,3,5,6-tetrafluorophenyl methacrylate (TFPM) was successfully synthesized via atom transfer radical polymerization (ATRP) technique. Controlled polymerization was achieved with the addition of CuBr₂ as deactivator, which decreased the reaction rate and minimized the premature termination. The controlled/''living'' polymerization behavior was supported by kinetic studies and the full chain extension for block copolymerization with 2-(dimethylamino) ethyl methacrylate (DMAEMA). Poly(TFPM) is an useful precursor for poly(methacrylamides) library syntheses. The active ester groups reacted with a variety of amines to produce a range of well-defined poly(methacrylamides), some of which would have been difficult to obtain by direct polymerizations of the methacrylamide monomers. Complete conversion to poly(methacrylamide) was achieved with unhindered primary amines. Substitution reactions with aromatic amines such as aniline did not occur under normal reaction conditions.
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Keywords: Controlled polymerization; 2,3,5,6-Tetrafluorophenyl methacrylate; Poly(TFPM)

1. Introduction

Active ester reagents are widely used for non-radioactive labeling [1,2] and as intermediates in amide library synthesis [3–5]. Polymeric reactive esters have been extensively studied by Ringdorf et al. in 1970s as pharmacologically active polymers which act as drugs themselves or as drug carriers [6–8]. The active esters react readily with a variety of nucleophiles such as primary and secondary amines. In most cases, the reactions are clean and quantitative and are widely used for conjugations with proteins and functionalized solid surfaces [9–12]. Polymers with reactive functional groups provide avenues for the subsequent modifications for specific applications [13]. Well-defined polymers are generally desirable as they possess more regular molecular architectures.

Controlled polymerizations of active esters, via atom transfer radical (ATRP) and reversible addition–fragmentation

chain-transfer (RAFT) polymerization techniques have mainly been focused on *N*-hydroxysuccinimide (NHS) ester. Polymers of NHS esters are useful precursors for polymer–drug conjugates [14] and as templates for poly(amides) syntheses [15]. Solid-supported active esters of NHS [1,16] and 2,3,5,6-tetrafluorophenyl methacrylate (TFPM) [17] are versatile in the field of library syntheses. In certain applications, such as in the case of [99mTc] ligand for pre-complexed antibody labeling, a less reactive TPFM ester is preferred [9].

Fluorine-containing polymers have always attracted a great deal of attention due to their interesting bulk and surface properties. Fluorinated polymers have superior oxidative stability, excellent oil and water repellency, high thermal stability and are highly resistant to chemicals [17–19].

Most of the fluorinated polymers reported have been synthesized via uncontrolled radical polymerization, an example of which is the recent report on the polymerizations of penta-flurophenyl acrylate/methacrylate using AIBN initiator [20]. Hvilsted et al. [21] has recently reviewed the current development of fluorinated polymeric materials with well-defined architectures synthesized via controlled radical polymerization

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techniques, namely ATRP, RAFT and nitroxide-mediated radical radical polymerization (NMP). ATRP has been the most versatile and is the dominating technique for the synthesis of well-defined fluorinated polymers [21–24].

In this paper, we report the controlled polymerization of 2,3,5,6-tetrafluorophenyl methacrylate (TFPM). We believe this is the first report on the successful controlled ATRP of a fluorinated phenyl methacrylate. The well-defined poly(TFPM) is an useful precursor for library synthesis of poly(methacrylamides) with narrow molecular weight distribution.

2. Experimental

2.1. Materials

Ethyl 2-bromoisobutyrate (EBrIB) (98%, Aldrich), 2,3,5,6-tetrafluorophenol (TFP) (97%, Aldrich), copper(I) chloride (CuCl) (99.995%, Aldrich), copper(I) bromide (CuBr) (99.999%, Aldrich), copper(II) bromide (CuBr$_2$) (99%, Aldrich), 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA) (97%, Aldrich), methacrylic acid (99%, Aldrich), 1,3-dicyclohexylcarbodiimide (99%, Aldrich), benzylamine (99%, Fluka), cyclohexylamine (99%, Fluka), *tert*-butylamine (99.5%, Fluka) and 4-dimethylaminopyridine (98%, Fluka) were used without further purification. 2-(Dimethylamino) ethyl methacrylate (DMAEMA) (98%, Merck) was purified by passing through an aluminum column and distillation under reduced pressure prior to use. All the solvents were freshly distilled before use.

2.2. Characterizations

NMR spectra were recorded using a Bruker DRX400 spectrometer. Gel permeation chromatography (GPC) was performed using an Agilent 1100 series GPC system equipped with a LC pump, PL gel 5 μm MIXED-C column and RI detector. The column was calibrated with narrow molecular weight polystyrene standards. The mobile phase was HPLC grade THF stabilized with BHT (stabilizer, 2,6-di-*tert*-butyl-4-methyl phenol) containing 1% triethylamine. The flow rate was usually at 1.0 mL/min.

2.3. Synthesis of TFPM

A 250 mL round bottle flask equipped with a calcium chloride drying tube was charged with TFP (10.0 g, 0.086 mol), dried THF (100 mL), methacrylic acid (11.0 mL, 0.129 mol) and 4-dimethylaminopyridine (3.52 g, 0.029 mol). The solution was stirred and cooled in an ice bath at 0 °C. 1,3-Dicyclohexylcarbodiimide (26.70 g, 0.129 mol) was then added over a period of 20 min. The reaction proceeded for another 30 min at 0 °C after which the ice bath was removed and the reaction mixture was stirred over night at room temperature. Dicyclohexylurea precipitated was removed by filtration. The solution was passed through a silicon gel column and eluted with *n*-hexane. The solvent was removed and the product was obtained as clear liquid. ^{1}H NMR (CDCl$_3$) δ: 6.96–7.05 (m, phenyl), 6.45 (d CH_2=C(CH$_3$)–) and 5.90 (d CH_2=C(CH$_3$)–), and 2.07 (s, methyl).

2.4. ATRP of TFPM catalyzed by EBrIB/CuBr/HMTETA system

In a typical polymerization experiment, CuBr (28.8 mg, 0.20 mmol) was added to a dry 25 mL Schlenk flask with a magnetic stirring bar under argon atmosphere. The flask was evacuated and flushed with argon three times. Degassed anisole (2.0 mL), TFPM (4.06 g, 17.08 mmol) and HMTETA (54.5 μL, 0.20 mmol) were added to the Schlenk flask using degassed syringes and the mixture was stirred for 10 min. The mixture was degassed by three freeze–pump–thaw cycles before EBrIB (29.5 μL, 0.20 mmol) was added. The reaction was then carried out, with constant stirring, in a thermostated bath at 90 °C for 0.5 h. The polymer was precipitated in ethanol as white powder.

2.5. ATRP of TFPM catalyzed by EBrIB/CuBr/HMTETA system with CuBr$_2$

The experimental procedure was similar to that without adding CuBr$_2$. A typical mixture containing CuBr (7.20 mg, 0.05 mmol), CuBr$_2$ (33.55 mg, 0.15 mmol), degassed anisole (2.0 mL), TFPM (2.03 g, 8.54 mmol), HMTETA (54.5 μL, 0.20 mmol) and EBrIB (29.5 μL, 0.20 mmol) was reacted at 90 °C for 2.5 h. The polymer was precipitated from ethanol as white powder. ^{1}H NMR (CDCl$_3$): δ 6.90–7.05 (br s, phenyl); 2.4–2.7 (br s, methylene); and 0.85–1.70 (m, methyl).

2.6. Copolymerization of DMAEMA using poly(TFPM)-Br macroinitiator

To a dry 25 mL Schlenk flask with a magnetic stirring bar under argon atmosphere, poly(PTFM)-Br ($M_n = 6300$; 0.5 g, 0.079 mmol) was added. The flask was evacuated and flushed with argon three times. Degassed anisole (0.7 mL), DMAEMA (0.85 mL, 5.04 mmol) and HMTETA (21.33 μL, 0.079 mmol) were added to the Schlenk flask with degassed syringes and the mixture was stirred for 10 min. The mixture was degassed by three freeze–pump–thaw cycles, after which CuBr (11.33 mg, 0.079 mmol) was added. The reaction proceeded with constant stirring at 90 °C for 2.5 h. The polymer was precipitated from hexane.

3. Results and discussion

3.1. ATRP of TFPM catalyzed by EBrIB/CuBr/HMTETA system

Polymerizations of TFPM initiated by EBrIB/CuBr/HMTETA system under various reaction conditions were investigated. All the reactions were carried out in anisole with the monomer concentration 50% (v/v) and [TFPM]$_0$:[EBrIB]$_0$:[CuBr]$_0$:[HMTETA]$_0$ = 85.4:1:1:1. The target M_n was 20,000. The results are presented in Table 1.

The reaction was found to be slow at 40 °C with only ∼15% monomer conversion after 4.5 h of reaction (Run A). At a higher temperature of 90 °C, 85% conversion was achieved after 5 h

Table 1
ATRP of TFPM initiated by EBrIB/CuBr/HMTETA in anisole solutions[a]

Run	Time (h)	Temperature (°C)	Conversion (%)	$M_{n(GPC)}$	$M_{n(th)}$[b]	M_w/M_n
A	4.5	40	14.6	1600	2900	1.48
B	9.0	60	50.9	1900	10,200	1.49
C	0.25	90	51.4	7400	11,300	1.88
D	5.0	90	85.0	8500	17,100	2.03
E[c]	3.0	90	81.3	8400	16,300	1.93

[a] Monomer/anisole 50% (v/v); $[EBrIB]_0:[CuBr]_0:[HMTETA]_0 = 1:1:1$ and $[TFPM] = 4.27$ M.
[b] $M_{n(th)} = ([TFPM]_0/[EBrIB]_0) \times MW_{TFPM} \times \text{conversion} + M_{EBrIB}$.
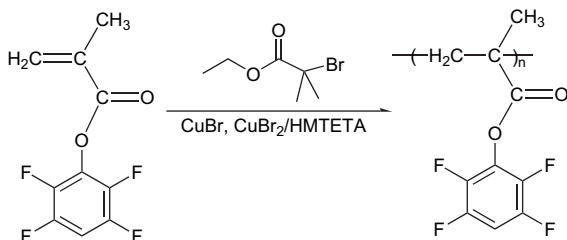[c] The CuCl was used instead of CuBr.

(Run D). All the polymerizations had poor control. The experimental M_n values were well below those of $M_{n(th)}$.

3.2. ATRP of TFPM catalyzed by EBrIB/CuBr/HMTETA system with added CuBr₂

The polymerization (Scheme 1) improved greatly with the addition of CuBr₂ into the system. With suitable CuBr/CuBr₂ ratio, controlled/"living" polymerizations of TFPM in bulk and in anisole solution were achieved. The results are summarized in Table 2. Run A, which is without the addition of CuBr₂ has poor control. Runs B–E are polymerizations with added CuBr₂, but maintaining total Cu concentration constant. It can be seen that $M_{n,GPC}$ values agree reasonably well with $M_{n(th)}$, and low M_w/M_n values were obtained. A trend of M_w/M_n decreasing with decreasing CuBr/CuBr₂ ratio from 0.85:0.15 (Run B) to 0.25:0.75 (Run E) is observed. When polymerized at a lower temperature of 60 °C, the M_w/M_n improved marginally to 1.28 (Run F), but the rate was considerably slower with only 44% conversion after 2.5 h.

Controlled polymerization was also observed in anisole solution, indicated by the good agreement of $M_{n(GPC)}$ with $M_{n(th)}$ and low M_w/M_n of 1.29. However, the reaction was slower than that in bulk, with 70% conversion after 2.5 h at 90 °C (Run G). Increasing the temperature to 100 °C increased the polymerization rate, but had little effect on M_w/M_n (Run H). The extra CuBr₂ increases the rate of the deactivation during the initial stage of the polymerization, which in turn decreases the growing radical concentration and hence minimizes the premature termination reaction.

The kinetic study was carried out at 90 °C in anisole with 1:1 (v/v) monomer:anisole and $[EBrIB]_0:[CuBr]_0:[CuBr_2]_0:[HMTETA]_0:[TFPM]_0 = 1:0.25:0.75:1.0:42.3$. Fig. 1 shows that % conversion increases steadily with time. The plot of $\ln([M_0]/[M])$ versus reaction time is linear up to high

Table 2
ATRP of TFPM initiated by EBrIB/CuBr/CuBr₂/HMTETA

Run[a]	Stoichiometry[b]	Temperature (°C)	Conversion (%)	M_n (GPC)	M_n (th)[c]	M_w/M_n
A	1:1.00:0:1:85.4	90	81.3	8400	16,300	1.93
B	1:0.85:0.15:1:85.4	90	93.9	18,700	18,600	1.53
C	1:0.75:0.25:1:85.4	90	91.7	17,800	18,400	1.44
D	1:0.50:0.50:1:85.4	90	89.1	18,100	17,800	1.37
E	1:0.25:0.75:1:85.4	90	81.0	16,300	16,100	1.32
F	1:0.25:0.75:1:85.4	60	43.8	6800	8800	1.28
G[d]	1:0.25:0.75:1:85.4	90	70.2	14,400	14,000	1.29
H[d]	1:0.25:0.75:1:85.4	100	88.4	19,800	17,600	1.30

[a] Runs A–F are polymerizations in bulk.
[b] Molar ratio of $[EBrIB]_0:[CuBr]_0:[CuBr_2]_0:[HMTETA]_0:[TFPM]_0$ and $[TFPM]=4.27$ M.
[c] $M_{n(th)} = ([TFPM]_0/[EBrIB]_0) \times MW_{TFPM} \times \text{conversion} + M_{EBrIB}$.
[d] In anisole solution.

conversion. Fig. 2 shows that M_n increases linearly with % conversion. Reasonably low M_w/M_n was maintained throughout the polymerization, confirming that the polymerization was indeed under controlled/"living" manner.

3.3. Effect of CuBr₂ concentration on the ATRP of TFPM

Increasing the concentration of Cu(II) in the reaction system decreases the polymerization rate. The first order kinetic plots with different $[CuBr_2]:[CuBr]$ ratios are shown in Fig. 3. The apparent rate constants (k_{app}) obtained from the slopes are presented in Table 3, showing that the increasing $[CuBr_2]:[CuBr]$ ratio decreases the polymerization rate. Increasing $[Cu(II)]$ reduces the polymerization rate and this minimizes radical coupling. Thus, a slower polymerization rate improves control, giving rise to a lower M_w/M_n (Table 3, Run C).

3.4. Kinetics of polymerization in bulk and in other solvents

The kinetics of polymerization of TFPM using EBrIB/CuBr/CuBr₂/HMTETA system at 90 °C in bulk and in DMF and DMSO solutions (monomer:solvent = 1:1 (v/v)) were

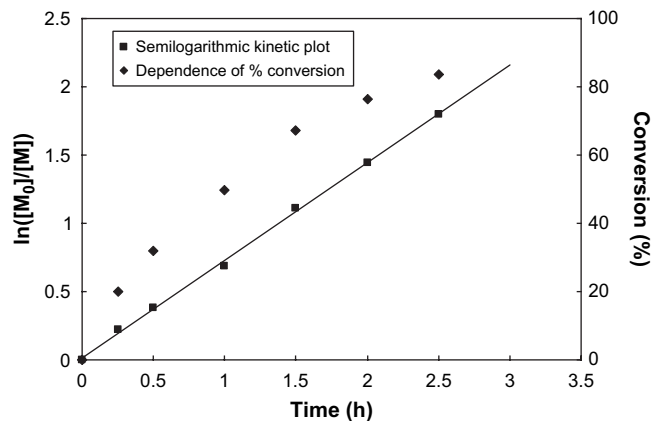Scheme 1. Synthetic route for the ATRP of TFPM.

Fig. 1. Semilogarithmic kinetic plot (■) and dependence of percentage conversion (◆) on time, for the ATRP of TFPM in anisole at 90 °C; monomer concentration 50% (v/v) at 90 °C; $[EBrIB]_0:[CuBr]_0:[CuBr_2]_0:[HMTETA]_0:[TFPM]_0 = 1:0.25:0.75:1:42.3$.
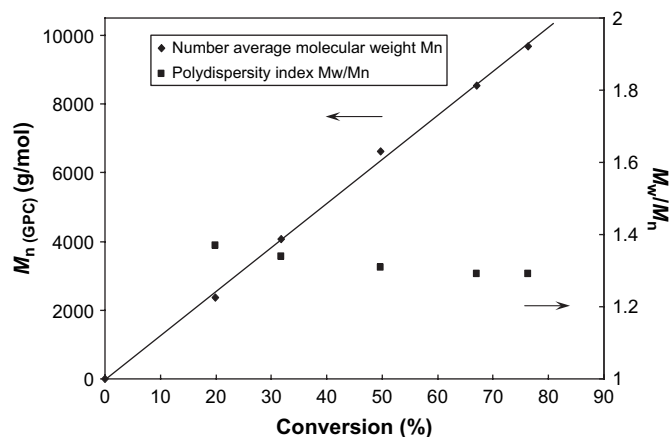
Fig. 2. M_n (◆) and M_w/M_n (■) as a function of percentage conversion for the ATRP of TFPM in anisole at 90 °C; monomer concentration 50% (v/v); [EBrIB]₀:[CuBr]₀:[CuBr₂]₀:[HMTETA]₀:[TFPM]₀ = 1:0.25:0.75:1:42.3.
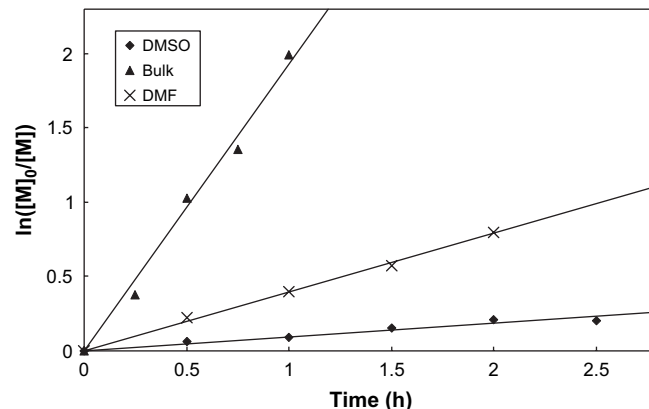

Fig. 4. Semilogarithmic kinetic plots, for the ATRP of TFPM in bulk and in solutions at 90 °C; monomer concentration 50% (v/v); [EBrIB]₀:[CuBr]₀:[CuBr₂]₀:[HMTETA]₀:[TFPM]₀ = 1:0.25:0.75:1:42.3, in bulk (▲), DMF (×), and DMSO (◆).

In solutions, the overall polymerization rates are solvent-dependent due to different solubility of the catalyst and the structure of copper species which could vary in different solvents [25–27].

3.5. Block copolymerizations of poly(TFPM) with DMAEMA

Poly(TFPM)-Br synthesized in anisole could successfully be used as macroinitiator for block copolymerization with DMAEMA, confirming the ''living'' chain ends of the polymer. For example, using a poly(TFPM)-Br (M_n 6300 and M_w/M_n 1.30) as the macroinitiator, and molar ratio [poly(TFPM)-Br]₀:[CuBr]₀:[HMTETA]₀:[DMAEMA]₀ = 1:1:1:63.4 at 90 °C, the conversion of DMAEMA reached 54% after 2.5 h. The $M_{n(GPC)}$ of the copolymer increased to 11,700 agreeing with the theoretical value ($M_{n(th)}$ = 12,200) calculated from the equation $M_{n(th)} = ([DMAEMA]_0/[poly(TFPM)\text{-}Br]_0) \times$ $MW_{DMAEMA} \times$ conversion + $M_{poly(TFPM)\text{-}Br}$. The M_w/M_n of the diblock copolymer increased slightly to 1.36. The increment of the molecular weight is indicated by the shift of the GPC traces (Fig. 5). The curve shifted towards the higher molecular weight, indicating the successful extension of the DMAEMA block. The average chain length of the second block was obtained by subtracting the M_n of the macroinitiator from the copolymer. The M_n of the block copolymer could also be calculated by ¹H NMR analysis from the intensity ratio of the aromatic proton at δ 7.02 ppm of poly(TFPM) block and ethylene group at δ 4.08 ppm of poly(DMAEMA) block.
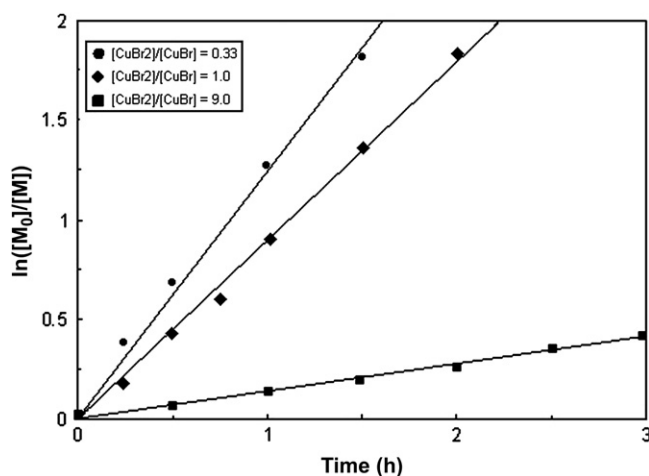

Fig. 3. Plots of ln[M]₀/[M] versus reaction time, for the ATRP of TFPM in anisole at 90 °C; monomer concentration 50% (v/v); [EBrIB]:[Cu$_{tot}$]:[HMTETA]:[TFPM] = 1:1:1:42.3, and [CuBr₂]/[CuBr] = 0.33 (●), 1.0 (◆), and 9.0 (■).

also studied. Good linear kinetic plots were obtained in all cases (Fig. 4). The apparent rate constants (k_{app}) are presented in Table 4.

The polymerization in bulk was fast and well controlled. The polymer had low polydispersity of 1.31 (Run A). Solution polymerizations in DMF and DMSO (Runs B and C) also proceeded under controlled manner with low polydispersity. The rates were slower than in bulk due to concentration effect.

Table 3
Apparent rate constants and M_w/M_n as a function of [CuBr]/[CuBr₂] in anisole at 90 °C

Run	[CuBr]/[CuBr₂]	M_w/M_n	$10^4 k_{app}$ (s⁻¹)
A	3.33	1.43	3.45
B	1.0	1.35	2.49
C	0.111	1.23	0.38

Monomer/anisole: 50% (v/v); [EBrIB]:[Cu$_{tot}$]:[HMTETA]:[TFPM] = 1:1:1:42.3.

Table 4
Polymerization of TFPM in bulk and in solutions at 90 °C

Run	Solvents	M_w/M_n	$10^4 k_{app}$ (s⁻¹)
A	In bulk	1.31	5.36
B	DMF	1.29	1.09
C	DMSO	1.33	0.28

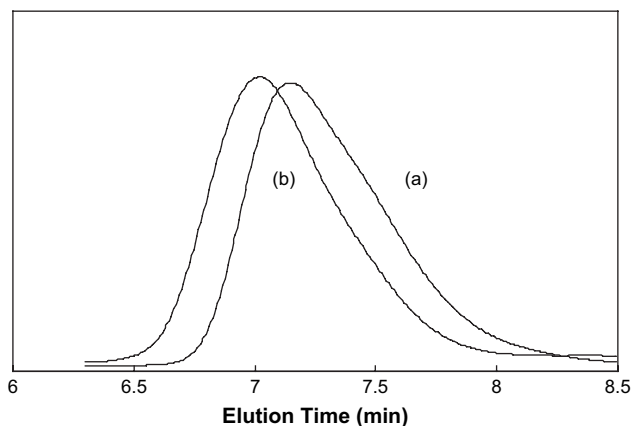For solutions, monomer/solvent: 50% (v/v); [EBrIB]₀:[CuBr]₀:[CuBr₂]₀:[HMTETA]₀:[TFPM]₀ = 1:0.25:0.75:1:42.3.

Fig. 5. GPC traces of (a) macroinitiator poly(TFPM)-Br (M_n 6300 and M_w/M_n 1.30) (b) poly(TFPM-b-DMAEMA) in anisole; monomer concentration 50% (v/v); [poly(TFPM)-Br]$_0$:[CuBr]$_0$:[HMTETA]$_0$:[DMAEMA]$_0$ = 1:1:1:63.36. Final product: M_n = 11,700, M_w/M_n = 1.36.
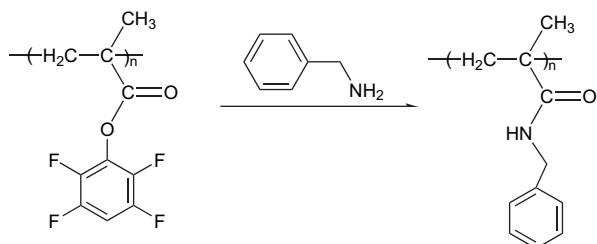
3.6. Poly(TFPM) as precursor polymer for poly(methacrylamides) library synthesis

The well-defined poly(TFPM) is an useful precursor for the syntheses of various poly(methacrylamides) with low polydispersity index. Poly(methacrylamides) can be obtained via aminolysis of poly(TFPM). A typical reaction with benzylamine (BzNH$_2$) is shown in Scheme 2. The results for the reactions with some amines are presented in Table 5. The substitution products were analyzed by ^{1}H NMR. Full conversions could be obtained with unhindered primary amines (Runs A, B, and C for BzNH$_2$, cyclohexylamine, and tert-butylamine, respectively). The results are consistent with those reported by Théato et al. for the reactions of primary amines with pentaflurophenyl(meth)acrylate polymers [20]. No reactions were observed for aniline (Run D) and amines with bulky groups, such as, 6-nitro-3-aminocoumarin (Run E), and the secondary amine N-phenyl piperazine (Run F).

The kinetics of the reactions between BzNH$_2$ and poly-(TFPM) were studied in DMF and dioxane with BzNH$_2$ in large excess; [TFPM]:[BzNH$_2$] at 1:50 and [BzNH$_2$] = 3.21 M. The pseudo-first order rate constants (k') were determined by using Eq. (1) [28],

$$\ln\left(\frac{[I]_\infty - [I]_t}{[I]_\infty - [I]_0}\right) = -k't \qquad (1)$$

where [I] represents the concentration of BzNH$_2$ reacted with TFPM to form substituted polymer BzNH-P. Hence

Table 5
Substitution reactions of poly(TFPM) with amines in anhydrous 1,4-dioxane solutions at 60 °C

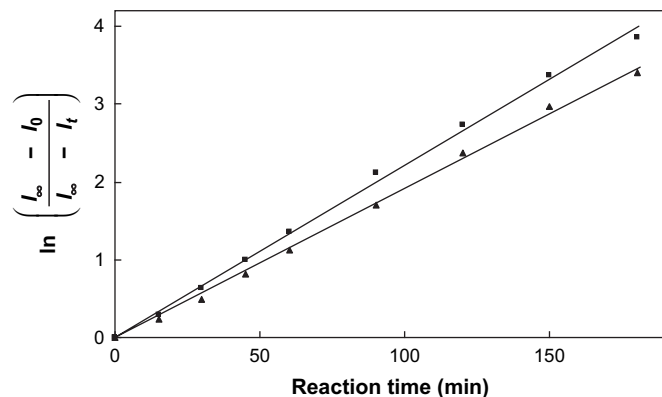| Run	Amines	[TFPM]: [amines]	Time (h)	Temperature (°C)	Conversion (%)
A	benzylamine (NH$_2$)	1:2	6	60	100
B	cyclohexylamine (NH$_2$)	1:2	6	60	100
C	tert-butylamine (H$_2$N)	1:3	24	80	100
D	aniline (NH$_2$)	1:3	24	80	0
E	6-nitro-3-aminocoumarin (O$_2$N, NH$_2$)	1:4	24	80	0
F	N-phenyl piperazine (N–NH)	1:4	24	80	0

Fig. 6. Kinetic plots for the substitution reaction of poly(TFPM) with BzNH$_2$ at 60 °C in DMF (■) and 1,4-dioxane (▲); [BzNH$_2$] = 3.21 M; molar ratio TFPM:BzNH$_2$ = 1:50.

$[I]_0$ = [BzNH-P]$_0$, $[I]_t$ = [BzNH-P]$_t$, and $[I]_\infty$ = [BzNH-P]$_\infty$ are the concentrations at reaction time zero, t, and infinity, respectively. The plots are shown in Fig. 6 and the pseudo-first order rate constants (k') obtained were $(3.70 \pm 0.07) \times 10^{-4}$ s^{-1} in DMF and $(3.20 \pm 0.06) \times 10^{-4}$ s^{-1} in 1,4-dioxane. The second order rate constants ($k_2 = k'/[$BzNH$_2]$) thus obtained were $(1.16 \pm 0.02) \times 10^{-4}$ M^{-1} s^{-1} in DMF and $(1.00 \pm 0.02) \times 10^{-4}$ M^{-1} s^{-1} in 1,4-dioxane. The results indicate that solvent has little effect on the aminolysis reactions of poly(TFPM).

4. Conclusions

Controlled ATRP of TFPM was achieved only with the addition of deactivator CuBr$_2$, without which the rate was too fast, leading to uncontrolled polymerization. Poly(TFPM)-Br macroinitiator successfully initiated the copolymerization of the second monomer DMAEMA. The successful block

Scheme 2. Aminolysis of poly(TFPM) with benzylamine.

copolymerization indicated that the chain ends of the macro-initiators had almost full bromine functionality, a consequence of ''living'' polymerization.

Poly(TFPM) is an useful precursor for polymer library synthesis. Well-defined poly(methacrylamides) could be obtained via aminolysis of poly(TFPM). Full conversion could be achieved with simple primary amines such as $BzNH_2$. Thus, well-defined poly(TFPM) serves as a useful template for the synthesis of other speciality polymers which would have been difficult to synthesize by direct controlled radical polymerizations.

Acknowledgements

References

[1] Adamczyk M, Fishpaugh JR, Mattingly PG. Bioorg Med Chem Lett 1999;9:217—20.
[2] Chang YT, Schultz PG. Bioorg Med Chem Lett 1999;9:2479.
[3] Salvino JM, Kumar NK, Orton E, Airey J, Kiesow T, Crawford K, et al. J Comb Chem 2000;2:691—7.
[4] Salvino JM, Gerard B, Ye HF, Sauvagnat B, Dolle RE. J Comb Chem 2003;5:260.
[5] Lee JW, Louie YQ, Walsh DP, Chang YT. J Comb Chem 2003;5:330.
[6] Batz HG, Franzmann G, Ringsdorf H. Angew Chem Int Ed 1972;11:1103—4.
[7] Batz HG, Ringsdorf H, Ritter H. Makromol Chem 1974;175:2229—39.
[8] Przybyski M, Fell E, Ringsdorf H. Makromol Chem 1978;179:1719—33.
[9] Sanchez OC, Mohammed A, Mier W, Graham K, Schuhmacher J, Arndt SO, et al. Bioconjugate Chem 2003;14:1209—13.
[10] Seifert S, Künstler JU, Schiller E, Pietzsch HJ, Pawelke B, Bergmann R, et al. Bioconjugate Chem 2004;15:856.
[11] Linton SD, Aja T, Armstrong RA, Bai X, Chen LS, Chen N, et al. J Med Chem 2005;48:6779.
[12] Jung SH, Son HY, Yuk JS, Jung JW, Kim KH, Lee CH, et al. Colloids Surf B Biointerfaces 2006;47:107.
[13] Patel MV, Dolia MB, Patel JN, Patel RM. React Funct Polym 2005;65:195.
[14] Godwin A, Hartenstein M, Muller AHE, Brocchini S. Angew Chem Int Ed 2001;40:594—7.
[15] Théato P, Kim JU, Lee JC. Macromolecules 2004;37:5475—8.
[16] Katoh M, Sodeoka M. Bioorg Med Chem Lett 1999;9:881—4.
[17] Kim YS, Lee JS, Ji Q, McGrath JE. Polymer 2002;43:7161.
[18] Imae T. Curr Opin Colloid Interface Sci 2003;8:307—14.
[19] Li K, Wu PP, Han ZW. Polymer 2002;43:4079.
[20] Eberhardt M, Mruk R, Zentel R, Théato P. Eur Polym J 2005;41:1569—75.
[21] Hansen NML, Jankova K, Hvilsted S. Eur Polym J 2007;43:255—93.
[22] Qiu J, Matyjaszewski K. Macromolecules 1997;30:5643.
[23] Jankova K, Hvilsted S. Macromolecules 2003;36:1753.
[24] Jankova K, Hvilsted S. J Fluorine Chem 2005;126:241.
[25] Pascual S, Coutin B, Tardi M, Polton A, Varon JP. Macromolecules 1999;32:1432.
[26] Matyjaszewski K, Nakagawa Y, Jasieczek CB. Macromolecules 1998;31:1527.
[27] Matyjaszewski K, Nakagawa Y, Jasieczek CB. Macromolecules 1998;31:1535—41.
[28] Frost AA, Pearson RG. Kinetics and mechanism. Tokyo, Japan: Wiley International Edition; 1952. p. 49.