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Initiator efficiency in ATRP: the tosyl chloride/CuBr/PMDETA system

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Abstract

The low efficiency of *p*-toluenesulfonyl chloride (TsCl) initiator for the polymerization of methyl methacrylate (MMA), when used in conjunction with *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine (PMDETA) and CuBr under atom transfer radical polymerization (ATRP) conditions was investigated. A major by-product in the formation of poly(methyl methacrylate) was identified as *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**) and accounted for approximately half of the initiator. Compound **5** was shown to form by the direct reaction of PMDETA and TsCl. In a model experiment equimolar amounts of TsCl, PMDETA and CuBr reacted at 80°C in *p*-xylene resulted in the formation of **5** and two other unsaturated sulfones 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester (**6**) and 2-[[4-methylphenyl)sulfonyl]methyl]-2-propenoic acid methyl ester (**7**), formed by the dehydrohalogenation and subsequent isomerization of an intermediate chloro-adduct, 1-(4-methylbenzenesulfonyl)-2-chloro-2-(methyl)methyl propionate (**2**). Molecular modeling predicted the unsaturated sulfone **7** was thermodynamically more stable than the higher conjugated sulfone **6** and this was confirmed by the isomerization of **6** to **7** at room temperature under mild basic conditions. The absence of **6** and **7** in the polymerization of MMA under ATRP conditions showed that in the early stages of polymerization in the presence of excess MMA, the intermediate chloro-adduct **2** is not formed.

Keywords: Initiators; Atom transfer radical polymerization (ATRP); Degree of polymerization (DP)

1. Introduction

In the past decade, the development of controlled/living radical polymerization techniques has made it possible to produce macromolecules of various architectures with well defined structures and narrow polydispersity. The techniques developed include nitroxide-mediated free radical polymerization (NMRP) [1–4], atom transfer radical polymerization (ATRP) [5–7] and reversible addition-fragmentation chain transfer polymerization (RAFT) [8,9]. ATRP emerged as a very versatile technique for conveniently preparing polymers with controlled molecular weights of low polydispersity and exhibiting good thermal stability. Various initiators and catalysts have been used in carrying out ATRP. *p*-Toluenesulfonyl chloride (TsCl) has been widely used since it is a 'universal' initiator capable of initiating a variety of different monomers [10]. It was reported to be particularly effective in the polymerization of styrene [11], methacrylates [12,13] and acrylates [14] due to the weak S–Cl bond [14]. The process of initiation was claimed to be free from side reactions and so result in polymerizations, which had no significant termination reactions normally associated with uncontrolled radical polymerizations [11]. The polydispersity of the polymer produced and the efficiency of the initiator are dependent on the type of ligand used. A tridentate tertiary amine, *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine (PMDETA) has emerged as a desirable choice of ligand, capable of complexing with CuBr to produce a soluble catalyst which improves the polydispersity of ATRP polymers while being commercially available and relatively inexpensive [15]. However, it has been reported that TsCl initiator, and catalyst consisting of PMDETA coordinated to CuCl, results in a low initiator efficiency of 50% for the polymerization of methyl methacrylate [16], 70% for *t*-butyl methacrylate [17] and as low as 25% for butyl methacrylate [18].

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In this paper, we investigate the possible reasons for the low TsCl initiation efficiency when using PMDETA and CuBr as catalyst. Model experiments were carried out to investigate the possible side reactions taking place during the initial initiation stage. Side products were isolated, identified and characterized and through model studies, a possible mechanism of TsCl side-reactions will be discussed.

2. Experimental

2.1. Materials

Methyl methacrylate (MMA, 99%) from Aldrich was washed three times with 5% w/w aq. NaOH solution and once with water. The solution was dried over MgSO4, filtered and distilled from CaH_2. *p*-Toluenesulfonyl chloride (TsCl, 99+%) (Aldrich) was dissolved in minimal chloroform, diluted with petroleum ether (bp 40–60°C), clarified with charcoal, filtered, concentrated and collected by filtration. Acetonitrile (99.7%), chloroform (99+%), methanol (99+%), tetrahydrofuran (THF, 99.7%), *p*-xylene (anhydrous, 99+%), triethylamine hydrochloride (98%), copper(I) chloride (97%) and copper(I) bromide (98%) (Aldrich) were used without further purification. Dichloromethane (DCM, 99+%) was dried over CaH_2 and distilled prior to use. *N*,*N*′,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine (PMDETA, 99%) from Aldrich was purified by passing through a neutral alumina column before use.

2.2. Characterization

GCMS analysis was performed on a Shimadzu GC-17A gas chromatograph equipped with a DB-5 capillary column (25 m, 5% phenyl siloxane) and coupled to a GCMS-QP5000 mass spectrometer. Initial temperature: 50 °C; initial time: 2.00 min; rate: 10 °C/min; final temperature: 280 °C; final time: 5 min; injector temperature: 240 °C.

GPC measurements were conducted in THF using a Waters 717 Plus Autosampler, a Waters 510 HLPC pump equipped with three Phenomenex phenogel columns (50, 10^3 and 10^5 nm) in series with a Wyatt Dawn F laser photometer operated at 90°, as well as in parallel with a Waters 410 differential refractometer (RI) and a Viscotek T50A differential viscometer, which together provided a triple detector system. Data acquisition and analysis were performed with the Viscotek TriSEC® software, and all three detectors were calibrated with PMMA standards of narrow molecular weight distribution and known intrinsic viscosity.

2.2.1. Synthesis of PMMA **4** under ATRP conditions

A mixture of methyl methacrylate (12.8 ml, 0.120 mol), CuBr (0.175 g, 1.22 mmol), PMDETA (0.25 ml, 1.22 mmol) and *p*-TsCl (0.233 g, 1.22 mmol) in *p*-xylene (16.9 ml) was added to a Schlenk flask and degassed by three freeze-pump-thaw cycles. The flask was then immersed in an oil bath at 80°C and heated for 18 h. A representative sample was taken (0.1 ml), diluted with methanol (0.9 ml), filtered and analyzed by GCMS, which showed only one product, which was later determined to be *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**). The remainder of the reaction mixture was dissolved in THF (100 ml) and precipitated into MeOH (2 l). The precipitate was collected by vacuum filtration and the precipitation repeated to afford PMMA macroinitiator **(4)** as a white solid (11.2 g, 92% yield based on MMA). GPC: $M_n = 19.8$ K, PD = 1.02, $[\eta]_w = 0.11$ dl/g, $Rg_w = 4.2$ nm. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.74 (d, $J = 8.2$ Hz, 0.011H, ArH), 7.36 (d, $J = 8.0$ Hz, 0.011H, ArH), 3.60 (s, 3H, OCH_3), 2.0–1.7 (m, 2H, CH_2), 1.02 (s, 0.45H, CH_3) 0.83 (s, 0.55H, CH_3).

2.2.2. Preparation of N,N-dimethyl-p-toluenesulfonamide (*5*)

A solution of *p*-TsCl (1.0 g, 5.3 mmol) and PMDETA (1.1 ml, 5.3 mmol) in *p*-xylene (20 ml) was stirred at 80°C overnight. The salt that formed was isolated by filtration (0.62 g). Solvent (50%) was removed by vacuum distillation and then an equivalent amount of methanol added. The reaction mixture crystallized on cooling and the solid collected by vacuum filtration. Recrystallization from methanol afforded **5** as pale yellow crystals (0.99 g, 95% yield), mp 81–82 °C (lit. [22] 83–83.5 °C). GCMS (EI) *m*/*z* (rel. int.): 199 (M+, 26%), 155 (16), 134 (3), 92 (21), 91 (100), 89 (6), 67 (3), 66 (3), 65 (30), 63 (8), 51 (5), 50 (3); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.66 (d, $J = 8.0$ Hz, 2H, ArH), 7.33 (d, $J = 8.0$ Hz, 2H, ArH), 2.68 (s, 6H, CH_3–N), 2.44 (s, 3H, Ar–CH_3). Acc. Mass (ES, Na^+): calculated for $C_9H_{13}NO_2SNa$, 222.0559, found 222.0559.

2.2.3. Reaction of equimolar amounts of TsCl, PMDETA, CuBr and MMA under ATRP conditions

Methyl methacrylate (131 μl, 1.22 mmol), CuBr (175 mg, 1.22 mmol), PMDETA (255 μl, 1.22 mmol) and TsCl (233 mg, 1.22 mmol) in *p*-xylene (16.9 ml) were added to a Schlenk flask and degassed by three freeze-pump-thaw cycles. The flask was back filled with argon and then heated at 80°C for 18 h. The reaction mixture was then cooled to ambient temperature. A sample (0.1 ml) was diluted with *p*-xylene (0.9 ml) for GCMS. The remainder of the reaction mixture was evaporated under reduced pressure to remove the solvent (*p*-xylene). The residue was dissolved in THF and filtered through a plug of neutral active alumina to remove the copper catalyst. TLC of the reaction mixtures (DCM, silica) showed several spots, which were isolated by radial chromatography. Co-elution of several of the products meant that quantification of each fragment was not possible, however, enrichment by repeated chromatography afforded fractions containing pure products, which were analyzed by NMR, ES-MS and Acc. Mass Spectrometry. The three major components of the reaction

mixture were compounds **5**–**7** in relative percentages of 48, 40 and 9%, respectively, with minor by-products accounting for 3% of the reaction mixture. Compound **5** from the previous experiment was analytically identical to the component isolated here. The analytical data for compounds **6** and **7** are shown below.

6: 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester [117659-27-5], mp 58–59 °C (lit. [19] 53–55 °C); GCMS (EI) *m/z* (rel. int.): 254 (M^+, 4%), 223 (9), 222 (41), 207 (10), 158 (6), 155 (23), 141 (5), 140 (9), 139 (100), 130 (21), 129 (10), 119 (25), 115 (11), 107 (6), 92 (12), 91 (76), 89 (9), 79 (6), 67 (8), 65 (53), 63 (12), 59 (22), 51 (8); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.81 (d, $J=8$ Hz, 2H, ArH), 7.37 (d, $J=8$ Hz, 2H, ArH), 7.22 (q, $J=2$ Hz, 1H, CH=C), 3.77 (s, 3H, CH_3–O), 2.45 (s, 3H, Ar–CH_3), 2.33 (d, $J=2$ Hz, 3H, CH_3–C=C); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 166.1 (CO), 145.1, (ArC), 140.6, 137.6 (CH=C), 137.5 (ArC), 130.0 (ArC), 127.7 (ArC), 53.0 (MeO), 21.7 (MeAr), 13.3 (MeCCO); Acc. Mass (ES, Na^+): calculated for $C_{12}H_{14}O_4SNa$, 277.0505, found 277.0506. Anal. calculated for $C_{12}H_{14}O_4S$: C, 56.68; H, 5.55; O, 25.17; S, 12.61, found: C, 57.27; H, 5.50, O, 25.31; S, 12.45.

7: 2-[[(4-methylphenyl)sulfonyl]methyl]-2-propenoic acid methyl ester [126234-89-7], mp 41–42 °C (lit. [20] 41–42.5 °C); GCMS (EI) *m/z* (rel. int.): 254 (M^+, 0.03%), 223 (2), 190 (9), 158 (4), 155 (32), 139 (8), 130 (8), 92 (10), 91 (100), 89 (5), 69 (7), 68 (23), 65 (30), 63 (7), 59 (17), 51 (6), 45 (7), 41 (15), 40 (22); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.70 (d, $J=8.4$ Hz, 2H, ArH), 7.31 (d, $J=8.4$ Hz, 2H, ArH), 6.46 (s, 1H, CH=C), 5.85 (s, 1H. CH=C), 4.11 (s, 2H, CH_2–SO_2), 3.56 (s, 3H, CH_3–O), 2.41 (s, 3H, $ArCH_3$); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 165.2, 145.8, 135.3, 133.4, 129.6, 128.9, 128.7, 57.6, 52.3, 21.5.

2.2.4. Reaction of equimolar amounts of TsCl, PMDETA and MMA

Methyl methacrylate (0.22 ml, 2.1 mmol), PMDETA (0.44 ml, 2.1 mmol) and TsCl (0.40 g, 2.1 mmol) in *p*-xylene (10 ml) were added to a Schlenk flask and degassed by three freeze-pump-thaw cycles. The flask was back filled with argon and then heated at 80°C for 24 h. The reaction mixture was cooled to ambient temperature and a sample (0.1 ml) diluted with *p*-xylene (0.9 ml) for GCMS. Only solvent, methyl methacrylate monomer and *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**) were identified by GCMS. The reaction mixture was reduced to dryness under reduced pressure to afford *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**) as a solid (0.39 g, 93% yield). Mp 81–82 °C (lit. [22] 83–83.5 °C).

2.2.5. Preparation of 1-(4-methylbenzenesulfonyl)-2-chloro-2-(methyl)methyl propionate (2) using a catalytic amount of Et_3N.HCl at 80 °C

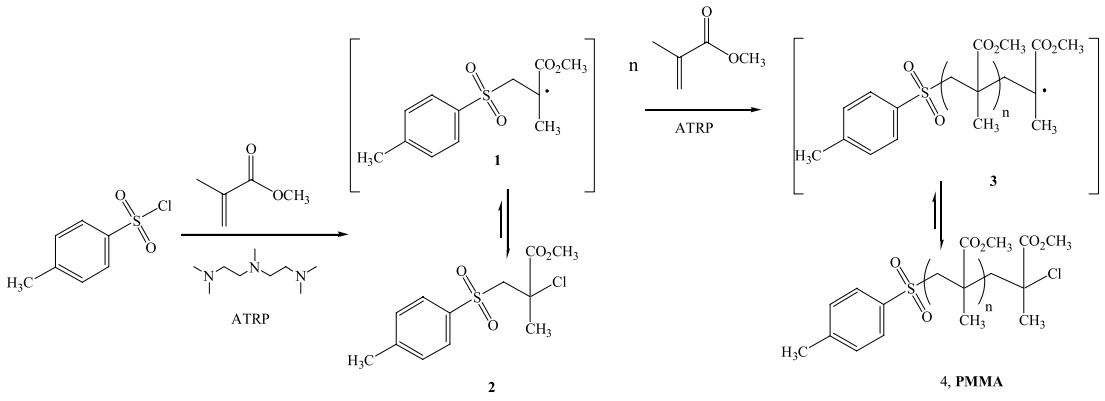
A mixture of MMA (5.0 ml, 47 mmol), *p*-toluenesulfonyl chloride (8.9 g, 47 mmol), Et_3N.HCl (155 mg, 1.1 mmol), CuCl (55 mg, 0.56 mmol), and acetonitrile (5.0 ml) in a Schlenk tube was degassed by three freeze-pump-thaw cycles and then purged with Argon. After heating at 80° for 20 h the mixture was cooled and a sample taken for GCMS analysis. This indicated the presence of unreacted TsCl and product **2**. Solvent (50%) was removed by vacuum distillation and then an equivalent amount of methanol added. Crystals separated on cooling and were isolated by vacuum filtration. Recrystallization from methanol afforded the product **2** as colorless crystals (8.57 g, 63% yield), mp 88–89 °C; GCMS (EI) *m/z* (rel. int.): 290 (M^+, 2%), 166 (5), 156 (5), 155 (37), 140 (4), 139 (33), 137 (10), 135 (37), 124 (6), 119 (4), 109 (2), 107 (6), 105 (4), 104 (2), 103 (5), 101 (11), 100 (31), 99 (20), 93 (3), 92 (22), 91 (100), 90 (3), 89 (8), 85 (9), 82 (3), 79 (8), 77 (7), 71 (3), 70 (7), 69 (86), 68 (5), 66 (2), 65 (41), 64 (3), 63 (9), 62 (2), 59 (41), 58 (2), 57 (5), 56 (6), 55 (12), 54 (2), 53 (4), 52 (2), 51 (9), 50 (4); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.77 (d, $J=8.1$ Hz, 2H, ArH), 7.36 (d, $J=8.1$ Hz, 2H, ArH), 4.12 (d, $J=14.1$ Hz, 1H, AA′, CH-$_2$), 3.81 (s, 3H, CH_3–O), 3.73 (d, $J=14.1$ Hz, 1H, AA′, CH-$_2$), 2.44 (s, 3H, CH_3–Ar), 2.00 (s, 3H, CH_3–C); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 169.1 (C=O), 145.2 (C_1), 137.2 (C_4), 130.0 ($C_{2,6}$), 127.9 ($C_{3,5}$), 65.4 (CH_2–S), 62.2 (*C*–Cl), 53.7 (CH_3–O), 26.7 (C–CH_{-3}), 21.6 (CH_3-Ar). Anal. $C_{12}H_{15}ClO_4S$ requires: C, 49.57; H, 5.20; O, 22.01; S, 11.03, found: C, 49.59; H, 5.24, O, 21.97; S, 11.10.

2.2.6. Preparation of 2 under ATRP conditions using a catalytic amount of PMDETA at 80 °C

A mixture of MMA (1.0 ml, 9.4 mmol), *p*-toluenesulfonyl chloride (1.8 g, 9.4 mmol), PMDETA (23 μl, 0.11 mmol), CuCl (11 mg, 0.11 mmol), and acetonitrile (1.0 ml) in a Schlenk tube was degassed by three freeze-pump-thaw cycles and then purged with Argon. After heating at 80°C for 16 h the mixture was cooled and a sample was taken for GCMS, which indicated the presence of unreacted TsCl (6%), unreacted MMA (5%), unsaturated sulfone **6** (11%) and product **2** (78%). Solvent (50%) was removed by vacuum distillation and then an equivalent amount of methanol added. Crystals separated on cooling and were isolated by vacuum filtration. Recrystallization from methanol afforded the product **2** as colorless crystals (1.89 g, 70% yield), mp 88–89 °C.

2.2.7. Preparation of 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester (6) from 1-(4-methylbenzenesulfonyl)-2-chloro-2-(methyl)methyl propionate (2) at room temperature (24 °C)

A mixture of **2** (1.0 g, 3.5 mmol), PMDETA (0.76 ml, 3.6 mmol), and DCM (40 ml) was added to a round bottom flask at 0°C and then stirred at room temperature (24 °C) for 5 h. GCMS analysis indicated the major product to be compound **6**. The reaction mixture was washed with HCl (1 M, 50 ml), sat. $NaHCO_3$ (50 ml), dried ($MgSO_4$), filtered and reduced to dryness to afford **6** as a colorless solid (0.72 g, 82%), mp 58–59 °C (lit. [19] 53–55°C). The



Scheme 1. Polymerization of MMA by ATRP in *p*-xylene at 80 °C: [MMA]=4 M; [CuBr]=[PMDETA]=[TsCl]=40.7 mM.

analytical data were identical to compound **6** isolated previously.

*2.2.8. Preparation of 2-[[(4-methylphenyl)sulfonyl]methyl]-2-propenoic acid methyl ester (**7**) from 1-(4-methylbenzenesulfonyl)-2-chloro-2-(methyl)methyl propionate (**2**) at room temperature (24 °C)*

A mixture of **2** (1.0 g, 3.5 mmol), PMDETA (0.76 ml, 3.6 mmol), and DCM (40 ml) was added to a round bottom flask at 0° and then stirred at room temperature (24 °C) for 2 days (48 h). GCMS analysis indicated the major product to be compound **7**. The reaction mixture was washed with HCl (1 M, 50 ml), sat. $NaHCO_3$ (50 ml), dried ($MgSO_4$), filtered and reduced to dryness to afford **7** as a colorless solid (0.83 g, 95%). The analytical data were identical to compound **7** isolated previously.

*2.2.9. Preparation of 2-[[(4-methylphenyl)sulfonyl]methyl]-2-propenoic acid methyl ester (**7**) from 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester (**6**) at room temperature (24 °C)*

A mixture of **6** (0.9 g, 3.5 mmol), PMDETA (0.76 ml, 3.6 mmol), and DCM (40 ml) was added to a round bottom flask at 0°C and then stirred at room temperature (24 °C) for 2 days (48 h). GCMS analysis indicated the major product to be compound **7**. The reaction mixture was washed with HCl (1 M, 50 ml), sat. $NaHCO_3$ (50 ml), dried ($MgSO_4$), filtered and reduced to dryness to afford **7** as a colorless solid (0.84 g, 96%). The analytical data were identical to compound **7** isolated previously.

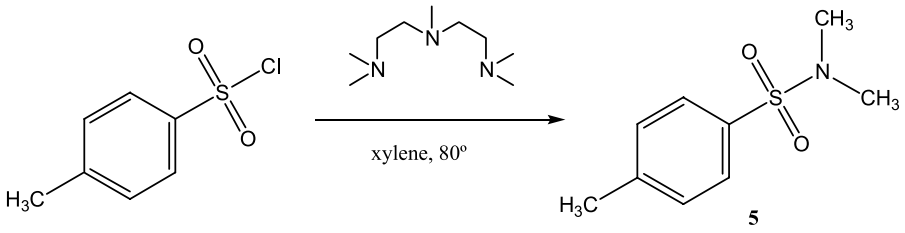
*2.2.10. Synthesis of PMMA **4** under ATRP conditions from **2** at 80°*

A mixture of MMA (12.8 ml, 0.12 mol), compound 2 (0.35 g, 1.2 mmol), CuBr (0.18 g, 1.2 mmol), PMDETA (0.25 ml, 1.2 mmol), in *p*-xylene (16.9 ml) was added to a Schlenck flask, degassed by three freeze-pump-thaw cycles. The flask was then purged with argon and heated at 80 °C overnight (20 h). The reaction mixture was diluted with THF (100 ml) and precipitated into MeOH (1 l). The precipitate was collected and dried under vacuum to afford PMMA **4** as a colorless solid (11.2 g, 91% yield). GPC: M_n=18.8 K, PD=1.02, $[\eta]_w$=0.11 dl/g, Rg_w=4.1 nm.

3. Results and discussion

When MMA is polymerized via ATRP with TsCl as initiator and CuBr/PMDETA as catalyst, the first step is the formation of initiator radical by dissociation of the chlorine atom from the tosyl group. As shown in Scheme 1, the addition of one monomer unit will yield a new radical **1**. Termination of **1** with chlorine from the complex can form the first adduct **2**. However, further reaction of MMA with radical **1** will propagate the polymer chain to form the propagated radical **3**. The polymer **4**, can be either isolated as the desired product or used as a macroinitiator to further chain extend or form a block polymer with a different monomer.

In one experiment, when MMA was polymerized via ATRP with CuBr/PMDETA and TsCl as initiator in *p*-xylene at 80 °C, PMMA **4** was obtained in 92% yield with narrow polydispersity (PD=1.02) (Scheme 1). However, the molecular weight of the polymer **4**, was twice that of the theoretical molecular weight; giving an initiator efficiency of around 50% with the rest of the tosyl functionality unaccounted for. This result is similar to that observed by Klumperman and co-workers [16–18]. If the significant loss of initiator were due to termination of growing polymer chains, then the polydispersity of the isolated polymer would not have been as low as we had obtained. In addition, chain extension of such a polymer would have shown substantially reduced conversion to a higher molecular weight polymer. However, chain extension of **4** formed a higher molecular weight polymer with an almost 100% macroinitiator efficiency. Therefore, it is apparent that side reactions were occurring at the early stages of the reaction resulting in by-products unable to take part in polymer formation. In order to investigate the fate of the initiator fragments in the formation of PMMA under our conditions, we designed a series of experiments to closely look at the



Scheme 2. Formation of *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**) in *p*-xylene at 80°C: [TsCl]=[PMDETA]=0.25 M.

by-products formed during the early stages in the polymerization process.

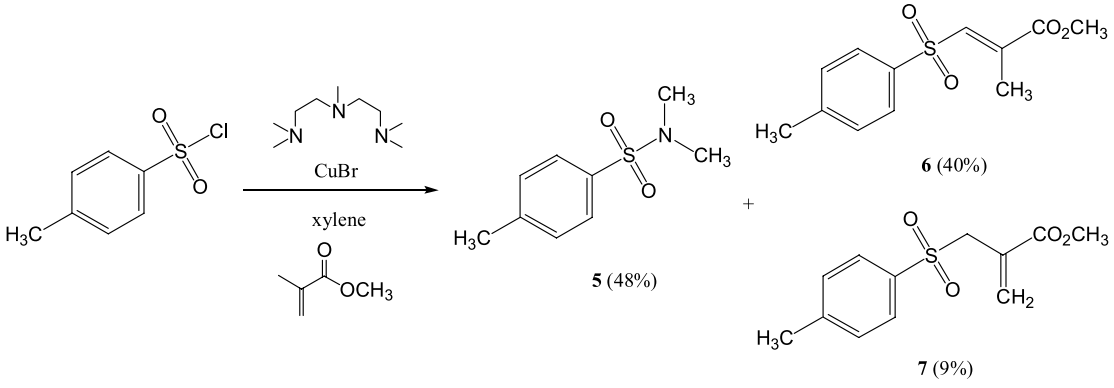
In a repeat of the preparation of PMMA, the polymer was isolated by precipitation into MeOH. This time the methanolic solution was concentrated under reduced pressure and analyzed by GCMS. A significant by-product formed in the reaction was *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**). The only possible source of the dimethyl amino functionality of compound **5** in the reaction mixture was from the PMDETA ligand.

To verify that the ligand was taking part in the reaction, a model experiment using equimolar amounts of TsCl and PMDETA in *p*-xylene was performed at 80°C overnight; a sulfonamide **5** was formed in 95% yield (Scheme 2). A second model experiment which included an added molar equivalent of CuBr and thus allowed for the formation of the CuBr/PMDETA catalyst complex, also resulted in a similar yield of the dimethylamino tosylate.

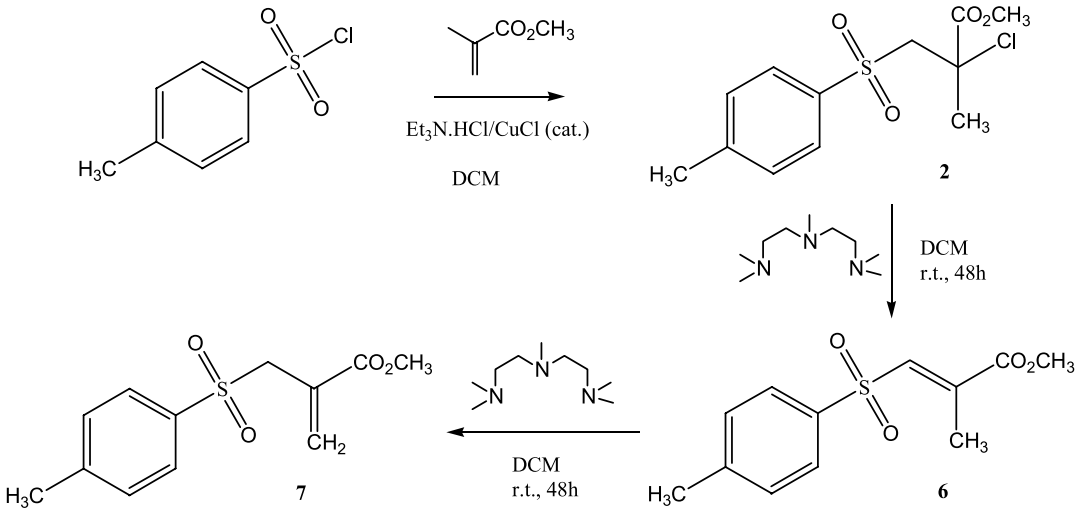
To quantify the extent of this reaction under ATRP conditions, equimolar amounts of TsCl, PMDETA, CuBr and MMA in *p*-xylene were reacted at 80°C for 18 h. Scheme 3 shows the products identified by GCMS analysis, which were determined to be *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**), 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester (**6**) and 2-[[(4-methylphenyl)sulfonyl]-methyl]-2-propenoic acid methyl ester (**7**) with relative peak areas of 48%, 40% and 9%, respectively. Compound **5** can be formed from the direct reaction of TsCl with PMDETA as shown in Scheme 2. Compounds **6** and **7**, which incorporate the moieties from the tosyl initiator and MMA, can be derived from compound **2**, the first adduct from the reaction of initiator with one MMA unit. The absence of compound **2**, expected from Scheme 3, can be explained by **2** further reacting to form **6**. Some of compound **6** then isomerises to form compound **7**. To investigate this hypothesis a pure sample of compound **2** was prepared by methodologies analogous to that used by Percec et al. [21], who prepared the *p*-methoxy equivalent of **2**. Thus, compound **2** was prepared in moderate yield (63%) from TsCl and MMA using a catalytic amount of $Et_3N.HCl$ and CuCl in dichloromethane (DCM), (Scheme 4).

In a subsequent reaction, compound **2** was reacted with a molar equivalent of PMDETA by stirring vigorously in DCM at room temperature for 5 h, and this afforded **6** in 98% yield. Compound **6**, is one of the products obtained in Scheme 3. The isolated compound **6** was then reacted further with a molar equivalent amount of PMDETA in DCM at room temperature over 4 days. Rearrangement of **6** in the presence of base slowly formed the β,γ-unsaturated sulfone **7** in quantitative yield, as shown in Scheme 4. The decomposition of compound **2** in the presence of base will initially form the elimination product **6**, which can then isomerise to form compound **7**. The absence of **2** in the initial product mixture, in the reaction of equimolar amounts of TsCl, MMA, PMDETA and CuBr (Scheme 3), is, therefore, understandable.

So far we have shown that a combination of TsCl and PMDETA under ATRP conditions led to a significant amount of by-products. We then performed a polymerization of MMA using the first adduct **2** as the initiator as



Scheme 3. Products formed by the reaction of equimolar amounts of TsCl, MMA, CuBr and PMDETA heated at 80°C in *p*-xylene for 18 h as determined by GCMS: [TsCl]=[MMA]=[PMDETA]=[CuBr]=0.07 M.



Scheme 4. Preparation of model compound **2** from TsCl and MMA; dehydrohalogenation of **2** under basic conditions to form α,β-unsaturated sulfone **6**; isomerization of **6** to form β,γ-unsaturated sulfone **7**.

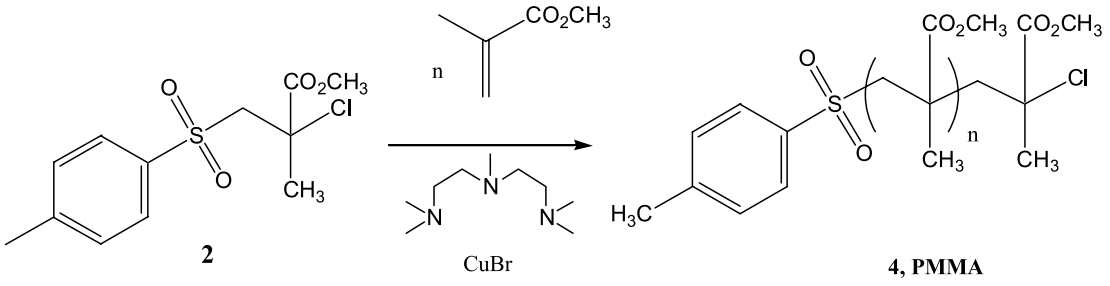
shown in Scheme 5. In this reaction it is not possible to form by-product **5**. We can also ascertain whether the rate of polymerization would be faster than the elimination reaction of **2**, leading to an increase in initiator efficiency. Here, a mixture of MMA, compound **2**, PMDETA and CuBr in the molar ratio of 100:1:1:1, respectively, was reacted at 80°C for 18 h. The polymer was isolated in 91% yield by precipitation into methanol. However, the molecular weight of the polymer obtained (M_n = 18.8 K) was almost twice that of the theoretical molecular weight (10 K). This suggests that the dehydrohalogenation of **2** into by-products, in the presence of base is accounting for approximately half of the initiator **2**. The rate of polymerization, at least at the early stages of the reaction, is in close competition with the elimination reaction to form compound **6**, which isomerises to form **7**.

The only by-product formed in the early polymerization of MMA under ATRP conditions was found to be the dimethylamino compound **5** accounting for approximately 50% of the initiator. If compound **2** were formed as an intermediate under ATRP conditions, we would have expected to detect compounds **2**, **6**, and **7** accounting for approximately one third of initiator consumption. However, the absence of these compounds **6** and **7**, suggests that when an excess of MMA is present, the preferred pathway is for multiple MMA groups to react with the radical **1** to form **3**, and not compound **2** (Scheme 6).

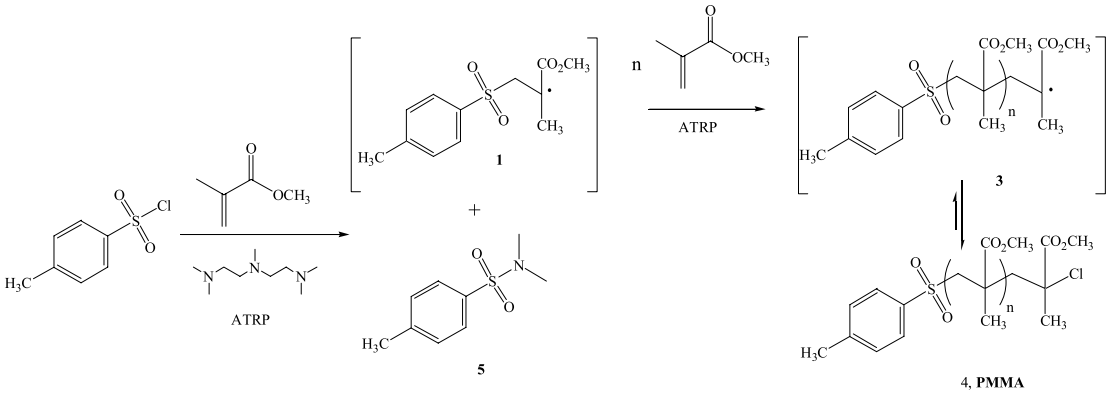
When only one equivalent of MMA is present and formation of **3** is unfavorable, then **1** adds chlorine to form compound **2**. Dehalogenation of the intermediate **2** forms α,β-unsaturated sulfone (**6**) which then isomerises to form β,γ-unsaturated sulfone (**7**) (Scheme 7).

Formation of the sulfone **6** follows Hofmann's rule, which states the double bond goes mainly toward the least highly substituted carbon. This mechanism is able to account for formation of **6** and **7** and the absence of **2** in the reaction of equimolar amounts of TsCl, MMA, PMDETA and CuBr under ATRP conditions.

The reason for elimination was further investigated by computer modeling using molecular mechanics calculations (MM2 Chemdraw3D). Energy minimization by this calculation at MM2 level showed isomers **6** and **7** to have total energies of 6.90 and 4.92 kcal/mol, respectively, (ΔG = −1.98 kcal/mol), with the former being the kinetically controlled product and the latter the thermodynamically controlled product. The pi-orbitals of both compounds were shown to lie in the same plane with only the sulfoxide



Scheme 5. ATRP of MMA using first chloro-adduct (**2**) as initiator in *p*-xylene at 80° for 20 h: $[MMA]_0$ = 4 M; [2] = [PMDETA] = [CuBr] = 4 mM.



Scheme 6. Possible pathways involved in polymerization of MMA under ATRP conditions.

double bonds out of the plane, giving rise to their higher stability than compound **2**, which had a less ordered arrangement of pi-orbitals (Fig. 1).

Polymerization of MMA was repeated under ATRP conditions with a catalytic amount of catalyst CuBr/PMDETA (0.1 M equiv. relative to compound **2**). The reduction in ligand formation was expected to reduce the amount of by-product **5** being formed, however, it had the added effect of reducing the rate of polymerization, since after 72 h only 22% of MMA had polymerized.

PMMA prepared according to Scheme 5 (M_n = 18.8 K) was used as a macroinitiator, by further reaction with MMA, PDMETA and CuBr at 80°C for 90 h. Here, chain extension of greater than 95% of the macroinitiator afforded PMMA with a molecular weight (M_n = 98 K) comparable to the theoretical molecular weight (M_{th} = 100 K) in 83% isolated yield. The high macroinitiator efficiency demonstrates the living nature of the macroinitiator and suggests that no side reactions producing unreactive by-product are occurring.

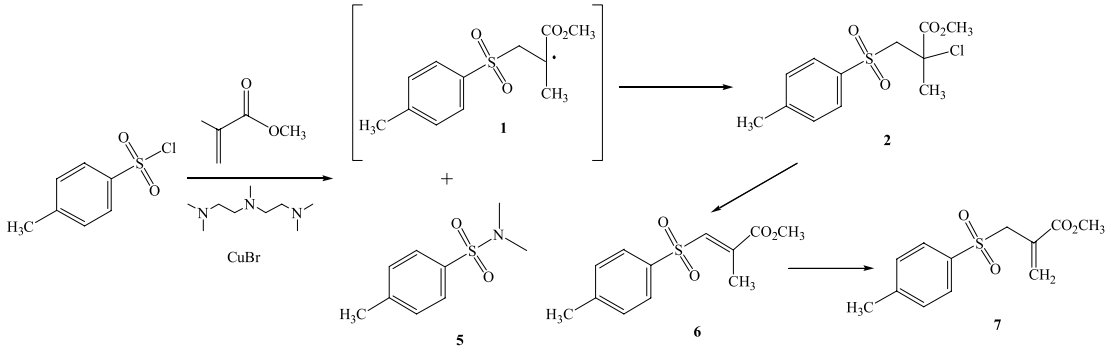
Formation of the tertiary amine **5** under ATRP conditions occurs via Hofmann elimination. The proposed mechanism for this reaction is given in Scheme 8, where it shows the formation of an intermediate quaternary salt which upon heating forms the tertiary amine **5**. A similar reaction was reported by Yoshida et al. [22], who observed the formation of compound **5**, during the tosylation of primary alcohols. Likewise Coessens and Matyjaszewski reported the reaction of tertiary amines, including PMDETA, with alkyl halides, resulted in a Hofmann elimination process [23,24]. However, they believed that when the ligand was complexed with a metal halide under ATRP conditions, the side-reactions would be too slow relative to the propagation reaction and would not be detected. In our investigation we found that even in the presence of an equimolar amount of metal halide (CuBr) and ligand (PMDETA), the formation of tertiary amine **5** was still observed and that the availability of free ligand had no effect. The choice of ligand is, therefore, important, since aromatic amines such as 2,2′-bipyridine and 4,4′-dinonyl-2,2′-bipyridine do not show any sign of amination of the tosyl initiator fragment and, therefore, are preferable [21,25–27].

4. Conclusions

Low initiator efficiency of TsCl when PMDETA is used as a ligand in the polymerization of MMA under ATRP conditions was investigated.

Under ATRP conditions in the presence of excess MMA monomer, apart from PMMA polymer the only significant by-product formed was *N*,*N*-dimethyl-*p*-toluenesulfonamide (**5**). The formation of **5** leads to approximately 50% initiator efficiency.

The reaction of molar equivalents of MMA, TsCl,



Scheme 7. Products formed from the reaction of molar equivalents of MMA, TsCl, under ATRP conditions.

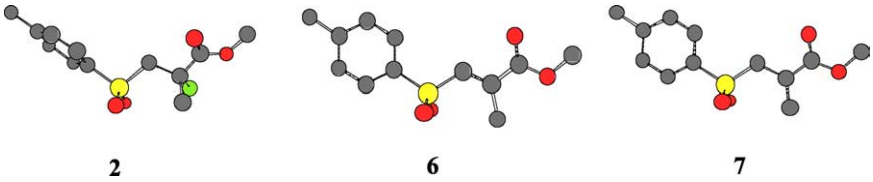
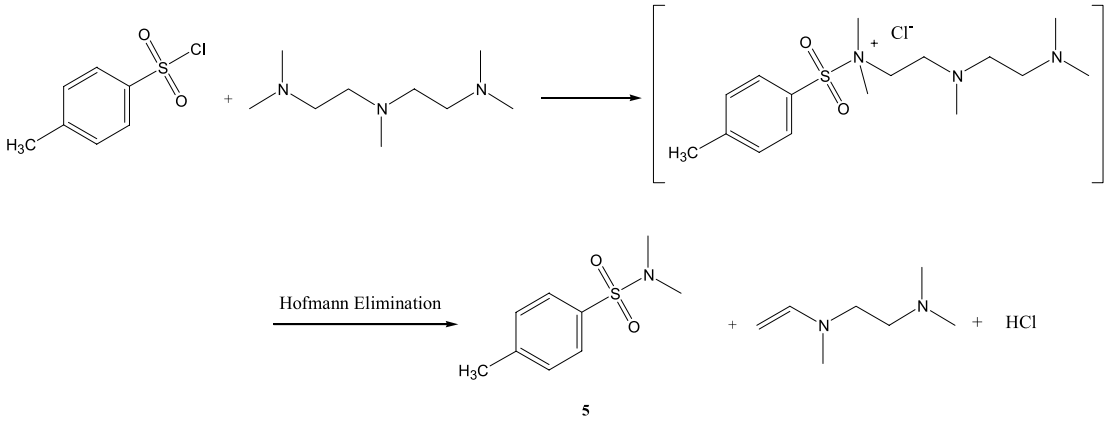


Fig. 1. Geometry of compounds **2**, **6**, and **7** generated by energy minimization using molecular mechanics (MM2).



Scheme 8. Proposed reaction of initiator TsCl with PMDETA under ATRP conditions.

PMDETA and CuBr led to the formation of by-product **5** as well as unsaturated sulfones 2-methyl-3-[(4-methylphenyl)sulfonyl]-2-propenoic acid methyl ester (**6**) and 2-[[(4-methylphenyl)sulfonyl]methyl]-2-propenoic acid methyl ester (**7**). The absence of the intermediate chloro-adduct, 1-(4-methylbenzenesulfonyl)-2-chloro-2-(methyl)methyl propionate (**2**) was explained by molecular modeling calculations which showed that compound **2** was less stable than the sulfones **6** and **7** and, therefore, preferentially eliminated HCl. Molecular modeling also showed **7** was slightly more thermodynamically stable than the sulfone **6**, which was verified by slow isomerization of **6** to **7** at room temperature under basic conditions.

When the chloro-adduct **2** was used to initiate polymerization, the initiator efficiency was still approximately 50% due to elimination of HCl. The absence of by-products **6** and **7**, indicates that in the presence of excess MMA the intermediate chloro-adduct **2** is not formed under ATRP conditions. That is, multiple additions of MMA occurs.

Polymerization of PMMA macroinitiator under ATRP conditions with PMDETA led to quantitative initiator efficiency with no observable by-products.

This study has provided a better understanding of initiator efficiency of TsCl under ATRP conditions using PMDETA. These findings can be used in designing polymerizations with better initiator efficiencies.

References

[1] (a) Solomon DH, Rizzardo E, Cacioli P. Eur Patent 135280 A2, 1985.
(b) Solomon DH, Rizzardo E, Cacioli P. US Patent 4581429, 1986.
[2] Georges MK, Veregin RPN, Kazmaier PM, Hamer GK. Macromolecules 1993;26:2987.
[3] Hawker CJ. J Am Chem Soc 1994;116:11185.
[4] Hawker CJ, Bosman AW, Harth E. Chem Rev 2001;101:3661.
[5] Kato M, Kamigaito M, Sawamoto M, Higashimura T. Macromolecules 1995;28:1721.
[6] Wang J-S, Matyjaszewski K. J Am Chem Soc 1995;117:5614.
[7] Matyjaszewski K, Xia J. J Chem Rev 2001;101:2921.
[8] Chiefari J, Chong YK, Ercole F, Krstina J, Jeffery J, Le TPT, et al. Macromolecules 1998;31:5559.
[9] Chiefari J, Rizzardo E. In: Matyjaszewski K, Davis T, editors. Handbook of radical polymerization. New York: Wiley; 2002. p. 629–90 [chapter 12].
[10] Percec V, Kim H-J, Barboiu B. Macromolecules 1997;30:8526.
[11] Percec V, Barboiu B. Macromolecules 1995;28:7970.
[12] Grimaud T, Matyjaszewski K. Macromolecules 1997;30:2216.
[13] Percec V, Kim H-J, Barboiu B. Macromolecules 1997;30:6702.
[14] Percec V, Barboiu B, Kim H-J. J Am Chem Soc 1998;120:305.
[15] Xia J, Matyjaszewski K. Macromolecules 1997;30:7697.
[16] Venkatesh R, Klumperman B. Macromolecules 2004;37:1226.
[17] Karanam S, Goossens H, Klumperman B, Lemstra P. Macromolecules 2003;36:3051.
[18] de Vries A, Klumperman B, de Wet-Roos D, Sanderson RD. Macromol Chem Phys 2001;202:1645.
[19] Nájera C, Baldó B, Yus M. J Chem Soc Perkin Trans I 1988;1029.
[20] Harvey I, Phillips ED, Whitham GH. Tetrahedron 1997;6493.
[21] Percec V, Barbiou B, Kim H-J. J Am Chem Soc 1998;120:305.
[22] Yoshida Y, Shimonishi K, Sakukura Y, Okada S, Aso N, Tanakura Y. Synthesis 1999;1633.
[23] Coessens V, Matyjaszewski K. J Macromol Sci, Pure Appl Chem 1999;A36:653.
[24] Matyjaszewski K, Xia J. J Chem Rev 2001;2921.
[25] Percec V, Barboiu B, Grigiras C, Bera TK. J Am Chem Soc 2003;125:6503.
[26] Percec V, Grigoras C, Kim H-J. J Polym Sci, Part A: Polym Chem 2004;42:505.
[27] Grigoras C, Percec V. J Polym Sci, Part A: Polym Chem 2005;43:319.