New Amine-Based Tripodal Copper Catalysts for Atom Transfer Radical Polymerization

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ABSTRACT: Three new amine-based tripodal copper complexes—tris(2-(diethylamino)ethyl)amine/CuBr (Et_6TREN/CuBr), 2,4-dimethyl-6-bis(2-(dimethylamino)ethyl)aminomethylphenoxy (*N*-tetramethyltriaminephenoxy) (Me_4TAPH/Cu^{II}), and *N*,*N*-bis[(2-pyridyl)methyl]-2-aminomethylpyrrolide (BPPY/Cu^I)—were prepared and investigated as ATRP catalysts in order to understand the effect of steric hindrance and the presence of a charged anionic group on the performance of catalysts based on branched tetradentate amine ligands in ATRP. Catalysts based on these ligands were evaluated for *n*-butyl acrylate (BA) polymerization, and their performance was compared with those of known analogues: Me_6TREN and *N*-tetraethyltriaminephenoxy (Et_4TAPH) copper complexes. When compared to Me_6TREN/CuBr-mediated polymerization, the more sterically hindered Et_6TREN/CuBr catalyst complex promoted a much slower and less controlled BA polymerization. This indicates that bulkiness around the metal center had a strong effect on the ATRP equilibrium. The Me_4TAPH copper(II) complex was also synthesized and used as an ATRP catalyst in a simultaneous reverse and normal initiation system. The rate of propagation was slightly lower, and control over the polymerization was poorer, than in a Me_6TREN-mediated polymerization. However, its catalytic performance was much better than the *N*-tetraethyl analogue, Et_4TAPH, copper complex. The much less hindered BPPY copper(I) complex promoted faster BA polymerization in DMF than Me_6TREN/CuBr-mediated polymerization, but the control over the polymerization was poor. These results indicate that steric hindrance is an important factor for developing new catalyst complexes for both high activity and control over ATRP. Selected complexes with charged ligands demonstrated enhanced ATRP activity.

Introduction

Controlled/“living” radical polymerization (CRP) is among the most versatile methodologies developed to control polymerization and create new polymer compositions and architectures. Several CRP processes have been extensively developed in the past decade,[1] including nitroxide-mediated polymerization (NMP), reversible addition−fragmentation chain transfer polymerization (RAFT), and atom transfer radical polymerization (ATRP). Among these CRP techniques, copper-based ATRP[2−4] is perhaps the most promising method because of catalytic nature and its synthetic versatility. In ATRP, a transition metal complex plays a crucial role in the establishment of a dynamic reversible activation/deactivation equilibrium. A number of transition metal complexes, including complexes based on early, middle, and late transition metals, have been investigated and developed as efficient ATRP catalysts.[4] In the ATRP process, the transition metal reversibly undergoes a one-electron oxidation and reduction that provides for activation and deactivation of the growing polymer chain end. The ligands provide solubility and adjust the redox potential of the metal center, offering appropriate reactivity and dynamics for the atom transfer. Thus, selection of the proper combination of transition metal and ligand is critical for success of ATRP.

Among the increasing number of ATRP catalyst systems examined, copper complexes remain perhaps the most promising due to their availability, versatility, and low catalyst cost. So far, a range of multidentate neutral nitrogen ligands was developed as active and efficient complexing agents for copper-mediated ATRP, including pyridine derivatives,[2] linear, branched, or cyclic aliphatic polyamines,[5,6] imine derivatives,[7] [8] picolylamine derivatives,[9] phenanthroline derivatives,[10] and terpyridine derivatives.[11] As a result of this research on these nitrogen base ligand systems, several criteria have been recognized as being beneficial when attempting to achieve high catalyst activity. The activity increases with increasing number of nitrogen coordination sites, $N1 \ll N2 < N3 < N4$, and with a decrease in the number of carbon atoms linking the nitrogen atoms, $C4 < C3 < C2$. Branched and cyclic polyamines usually possess higher activity than linear polyamines. As a result, the tris(2-(dimethylamino)ethyl)amine (Me_6TREN) copper complex is presently the most active ATRP catalyst that has been developed.[6,12]

In general, K_{ATRP} correlates with the overall strength of complexation; stronger coordination gives better K_{ATRP}.[13] One possible option, to further enhance the bond strength between the transition metal and the ligand, is introduction of an anionic charged group into the ligand. An anionically charged ligand might coordinate with the copper atom stronger, and the resulting complex could possibly possess higher activity than catalysts having neutral ligands. Thus, we have attempted to introduce a charged group into a branched tetradentate ligand complex, which is a potentially highly active ATRP catalyst. Before this investigation, we have reported synthesis and catalytic performances of the neutral *N*-tetraethyltriaminephenoxy (Et_4TAPH) copper(I) complex.[14] This copper complex contains both a branched amine group and a charged group. Thus, it could be anticipated that such a complex could possess higher activity than Me_6TREN copper complexes. In

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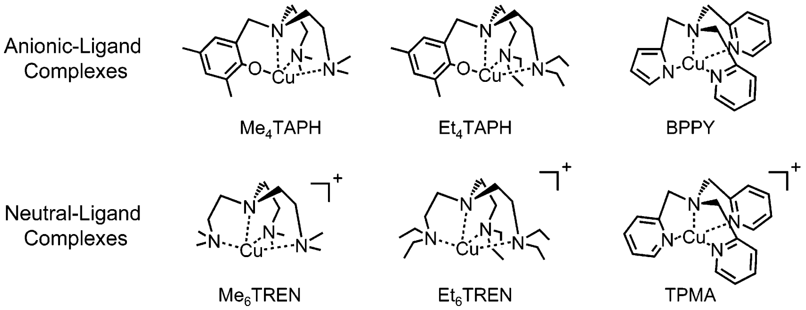
Scheme 1. Tripodal Anionic and Neutral Ligand Complexes



fact, this neutral copper complex did promote relatively fast acrylate polymerization; however, it resulted in a less controlled polymerization. The molecular weight was higher than expected from quantitative initiation, and the polymer displayed a broad molecular weight distribution. Both observations indicated slow deactivation. The level of control over polymerization was dramatically improved when a small amount of an efficient deactivator, such as Me$_6$TREN/CuBr$_2$, was added.[14] Hence, although an interesting dual ATRP catalyst system was discovered by introduction of charged group into a branched tetradentate ligand, the concept was not fully successful at developing a new highly active catalyst in and of itself.

After the investigation of the dual catalyst system, we paid increased attention to the steric effects of the alkyl groups on the amine nitrogen atoms. Even in the TREN-based catalyst system, catalytic activity was significantly reduced compared to that of Me$_6$TREN when bulky groups were introduced at the nitrogen atom, e.g., (acrylate)$_6$TREN.[15] Therefore, in this study, we report on the investigation of three new tripodal copper complexes—tris(2-(dimethylamino)ethyl)amine (Et$_6$TREN), 2,4-dimethyl-6-bis(2-(dimethylamino)ethyl)-aminomethylphenoxy (*N*-tetramethytriaminephenoxy) (Me$_4$TAPH), and *N,N*-bis[(2-pyridyl)methyl]-2-aminomethyl pyrrolide (BPPY) copper complexes—as ATRP catalysts for *n*-butyl acrylate polymerization. We compared their catalytic activity and the level of control over polymerization to the performance of analogous copper catalysts, such as Me$_6$TREN, Et$_4$TAPH, and TPMA copper complexes (Scheme 1). Dramatic steric effects and charged group effects were observed for these catalyst systems.

Experimental Section

Characterization. ^{1}H NMR spectra were collected with a Bruker 300 MHz ^{1}H NMR using CDCl$_3$ as a solvent. Elemental analyses were performed by Midwest Microlab, LLC. Monomer conversion was determined by gas chromatography using a Shimadzu GC 14-A gas chromatograph equipped with a FID detector and a J&W Scientific 30 m DB WAX Megabore column. Molecular weight and molecular weight distribution of polymers were determined by GPC using PSS column (Styrogel 10^5, 10^3, 10^2 Å) with RI detectors. GPC was performed using THF as an eluent at a flow rate of 1 mL/min. Linear polystyrene standards were used for calibration of poly(*n*-butyl acrylate). Theoretical molecular weights were calculated using the following equation:

$$M_{\mathrm{n,th}} = ([\text{monomer}]_0/[\text{initiator}]_0) \times \text{conversion} \times \text{MW(monomer)} + \text{MW(initiator)} \quad (1)$$

Materials. Copper(I) bromide,[16] tris(2-(dimethylamino)-ethyl)amine (Me$_6$TREN),[12] *N*-tetraethyltriaminephenoxy (Et$_4$TAPH) copper(I) complex,[14] and *N,N,N′,N′*-tetramethyldiethylenetriamine[17] were prepared and purified as detailed in previous reports. 2,2′-Azobis(isobutyronitrile) (AIBN) was recrystallized from diethyl ether. *n*-Butyl acrylate (BA) was passed through a column filled with neutral alumina to remove stabilizer, dried over calcium hydride, and distilled under reduced pressure before use. Acetonitrile was distilled over calcium hydride under nitrogen prior to use. All other reagents and solvents were used as received.

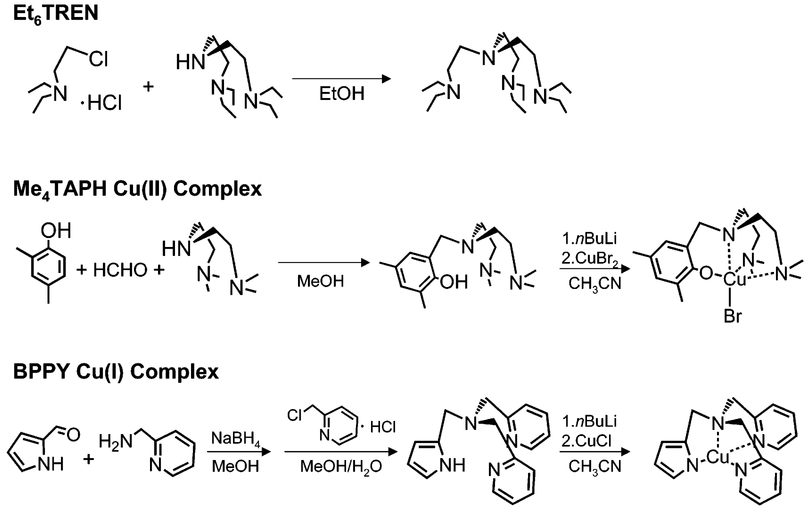
Synthesis of Tris(2-(diethylamino)ethyl)amine (Et$_6$TREN). Et$_6$TREN was synthesized by a procedure similar to those reported before.[18] *N,N,N′,N′*-Tetraethyldiethylenetriamine (90% purity, 2.5 g, 10.4 mmol) in ethanol (10 mL) was added dropwise, under nitrogen, to a solution of 2-(diethylamino)ethyl chloride hydrochloride (1.8 g, 10.5 mmol) in ethanol (20 mL) at 80 °C, and the resulting mixture was stirred for 2 h at this temperature. The reaction mixture turned from colorless to light brown as the reaction progressed. After the reaction, ethanol was removed by evaporation. The remaining brown oil was dissolved in water, and the pH of the solution was adjusted to ~14 by addition of an aqueous NaOH solution. A yellow oil separated out and was extracted with ether (3 × 30 mL). The combined ether extracts was dried over MgSO$_4$. After evaporation of volatiles, including ether and unreacted *N,N,N′,N′*-tetraethyldiethylenetriamine under vacuum, Et$_6$TREN was obtained as a yellow oil in 34% yield. ^{1}H NMR (300 MHz, CDCl$_3$): δ 0.98 (t, 18 H), 2.49 (q, 12 H), 2.49−2.59 (m, 12 H). Anal. Calcd for $C_{18}H_{42}N_4$: C, 68.73; H, 13.46; N, 17.81. Found: C, 68.80; H, 13.19; N, 17.54. $d = 0.86$ g/mL.

Synthesis of 2,4-Dimethyl-6-bis(2-(dimethylamino)-ethyl)aminomethylphenol.[14] Paraformaldehyde (95% purity, 0.35 g, 11.1 mmol) and *N,N,N′,N′*-tetramethyldiethylenetriamine[17] (1.75 g, 11.0 mmol) were placed in a 50 mL round-bottom flask and stirred at 80 °C for 1 h. A solution of 2,4-dimethylphenol (1.35 g, 10.9 mmol) in methanol (7 mL) was then added to the resulting yellow oil, and this solution was stirred for 24 h under gentle reflux. After the reaction was complete, the methanol was removed through evaporation and the residual oil was purified by silica gel column chromatography using CH$_2$Cl$_2$/methanol = 9/1 v/v as eluent. After evaporation of the solvent, the desired compound was obtained as a yellow oil in 79% yield. ^{1}H NMR (300 MHz, CDCl$_3$) δ: 2.20 (s, 18 H), 2.45 (t, 4 H), 2.65 (t, 4 H), 3.66 (s, 2 H), 6.61 (s, 1 H), 6.83 (s, 1 H).

Synthesis of 2,4-Dimethyl-6-bis(2-(dimethylamino)-ethyl)aminomethylphenoxycopper(II) Complex (Et$_4$TAPH Copper(II) Complex). Synthesis of the copper complex was performed using standard Schlenk techniques. 2,4-Dimethyl-6-bis(2-(dimethylamino)ethyl)aminomethylphenol (587 mg, 2.0 mmol) was added to a 50 mL Schlenk flask, degassed under vacuum, and placed under nitrogen. This phenol compound was dissolved in acetonitrile (15 mL), and then a solution of 2.5 N *n*-butyllithium in hexane (0.8 mL, 2.0 mmol) was added at 0 °C. After the addition of *n*-butyllithium, the reaction mixture was allowed to warm to room temperature and stirred for 2 h.

The resulting white slurry was added to a solution of CuBr$_2$ (467 mg, 2.0 mmol) in acetonitrile (10 mL) at 0 °C. The reaction mixture became homogeneous and purple in color. The solution was allowed to warm to room temperature and stirred for 3 h. After the reaction completed the solvent was removed under

Scheme 2. Synthesis of Et_6TREN Ligand, Me_4TAPH Copper(II) Complex, and BPPY Copper(I) Complex



vacuum. The resulting purple semisolid was used as an ATRP catalyst without any purification. The content of the copper(II) complex was estimated to be 83.4 wt %. This purple semisolid was highly soluble in polar solvents, e.g., acetonitrile and DMF, but poorly soluble in nonpolar solvents such as toluene and hexane. It is also highly hygroscopic, plausibly due to the presence of LiBr.

Synthesis of *N*,*N*-Bis[(2-pyridyl)methyl]-2-aminomethylpyrrole (BPPY). Pyrrole-2-carboxaldehyde (2.77 g, 2.85×10^{-2} mol) was dissolved in methanol (30 mL), and a solution of 2-(aminomethyl)pyridine (3.12 g, 28.5 mmol) in methanol (20 mL) was added. The mixture was stirred at room temperature for 3 h followed by heating to reflux for 30 min. The resulting yellow solution was cooled in ice bath, and then $NaBH_4$ (5.00 g, 13.2 mmol) was gradually added under nitrogen. Gas generation was observed. After addition of $NaBH_4$, the mixture was stirred at 0 °C for 30 min, at room temperature for 30 min, and then at 50 °C for 2 h. After the reaction was completed, water (5 mL) was added to decompose the remaining $NaBH_4$, and then the mixture was partially concentrated. Water (50 mL) was added to the mixture, and the organics were extracted with ether (3×50 mL). The ether layers were combined and dried over $MgSO_4$, and then volatiles were removed by evaporation. *N*-(2-Pyridyl)methyl-2-(aminomethyl)pyrrole was obtained as a colorless oil in 86% yield: ^1H NMR (300 MHz, $CDCl_3$) δ: 3.85 (s, 2H), 3.92 (s, 2H), 6.07 (m, 1H), 6.16 (dd, 1H), 6.76 (m, 1H), 7.20 (m, 1H), 7,28 (t, 1H), 7.67 (td, 1H), 8.59 (dt, 1H).

Na_2CO_3 (7.5 g, 70.8 mmol) was added to a solution of *N*-(2-pyridyl)methyl-2-(aminomethyl)pyrrole (4.60 g, 24.1 mmol) in methanol/water (25 mL/12.5 mL). A solution of 2-picolyl chloride hydrochloride (3.96 g, 24.1 mmol) in methanol (40 mL) was added to the suspension at room temperature and stirred overnight. After filtration, the filtrate was concentrated. Water (20 mL) was added to the solution, and organics were extracted into ether (3×25 mL). The combined ether layers were dried over $MgSO_4$ and then evaporated. The resulting brown oil was purified through column chromatography (SiO_2, CH_2Cl_2/MeOH = 9/1 v/v). After evaporation, the desired compound was obtained as a brown oil in 70% yield. ^1H NMR (300 MHz, $CDCl_3$) δ: 3.67 (s, 2H), 3.83 (s, 4H), 6.07 (m, 1H), 6.17 (dd, 1H), 6.86 (m, 1H), 7.21 (m, 2H), 7,47 (d, 2H), 7.69 (td, 2H), 8.59 (dt, 2H).

Synthesis of *N*,*N*-Bis[(2-pyridyl)methyl]-2-aminomethylpyrrolidecopper(I) Complex (BPPY Copper(I) Complex). Synthesis of the copper complex was performed using standard Schlenk techniques. *N*,*N*-Bis[(2-pyridyl)methyl]-2-(aminomethyl)pyrrole (0.90 g, 3.23 mmol) was dissolved in CH_3CN (15 mL), and 2.5 N *n*-BuLi (hexane solution, 1.29 mL, 3.23 mmol) was then added to the solution at 0 °C and stirred for 2 h at room temperature. A solution of CuCl (0.32 g, 3.23 mmol) in CH_3CN (15 mL) was added to the resulting light brown solution at 0 °C, and the mixture was stirred for 2 h at room temperature. A deep red solid precipitated out of the reaction. This solid was separated through centrifuge, washed with CH_3CN, and then dried under vacuum. 0.2 g of deep red solid was obtained.

ATRP of *n*-Butyl Acrylate (BA). A typical ATRP polymerization procedure was performed as follows. Solid materials, such as CuBr, AIBN, and copper complex, were placed in a 25 mL Schlenk flask, and then the flask was evacuated and backfilled with nitrogen three times. BA, anisole as internal standard, and, if any, Me_6TREN or Et_6TREN were successively added to the flask after degassing by bubbling with nitrogen for 30 min. Finally an initiator, methyl 2-bromopropionate, was added. The resulting mixture was heated to polymerization temperature to start the polymerization. Samples were taken periodically via a syringe to follow the kinetics of the polymerization process. The samples were diluted with THF followed by filtration through a Gelman Acrodisc 0.2 μm PTFE filter prior to the analysis by gas chromatography (GC) and gel permeation chromatography (GPC).

Results and Discussion

BA Polymerization with Et_6TREN/CuBr. To investigate steric effect of a bulkier alkyl group in the TREN-based catalyst system, tris(2-(diethylamino)ethyl)amine (Et_6TREN) was synthesized and evaluated as ligand for copper-mediated ATRP. Et_6TREN was prepared through the N-alkylation reaction of *N*,*N*,*N′*,*N′*-tetraethyldiethylenetriamine with 2-(diethylamino)ethyl chloride hydrochloride.[18] Both starting materials are commercially available. Et_6TREN was obtained as a yellow oil in 34% yield (Scheme 2). The catalytic behavior was compared to that of a Me_6TREN-mediated polymerization.

The initial BA polymerization was conducted using 10 mol % catalyst vs initiator with $[BA]_0/[I]_0 = 200/1$ at 60 °C. Polymerization was performed essentially in bulk, though 5 vol % anisole vs monomer was used as an internal standard for GC analysis. A Me_6TREN/CuBr-mediated BA polymerization was also conducted under the same conditions to compare their catalytic performance. The results of both polymerization are summarized in Table 1 along with other results from this series of experiments. When Me_6TREN/CuBr was used as a catalyst, a fast and well-controlled polymerization was observed, as reported earlier.[6,12] Monomer conversion reached 89% in 2 h, and molecular weight agreed perfectly with predicted values throughout the polymerization (Figures 1 and 2). The molecular weight

Table 1. Conditions and Results for ATRP of BA Using Me_6TREN, Et_6TREN, and Et_4TAPH Cu(I) Complex[a]

expt	catalyst	$[I]_0/[Cu/L]_0$	*t* (h)	conv (%)	M_n ($\times 10^{-4}$)	$M_{n,theo}$ ($\times 10^{-4}$)	M_w ($\times 10^{-4}$)	M_w/M_n
1	Et_6TREN/CuBr	1/0.1	4	15.8	2.27	0.42	8.65	3.82
2	Et_6TREN/CuBr	1/1	48	68.7	1.71	1.78	2.18	1.28
3	Et_4TAPH Cu(I)	1/1	8	72.5	2.89	2.81	5.00	1.73
4	Me_6TREN/CuBr	1/0.1	2	88.7	2.26	2.29	2.54	1.12

[a] Polymerization conditions: initiator = methyl 2-bromopropionate, temperature = 60 °C, $[BA]_0$ = 6.64 M, $[BA]_0/[I]_0$ = 200/1, BA/anisole = 1/0.05 v/v.

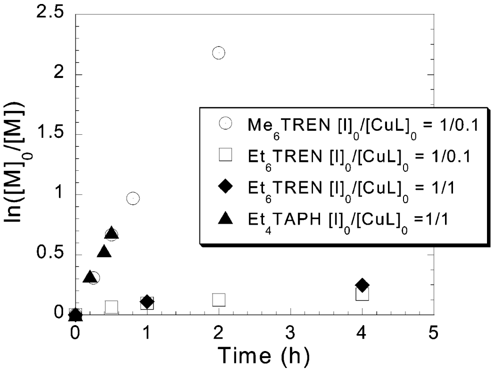


Figure 1. Kinetic plots for the polymerization of BA using Me_6TREN, Et_6TREN, and Et_4TAPH copper(I) complexes. See Table 1 for polymerization conditions.

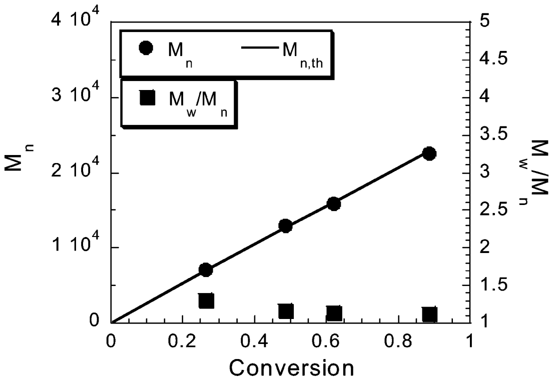


Figure 2. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA using Me_6TREN/CuBr. See Table 1 for polymerization conditions.

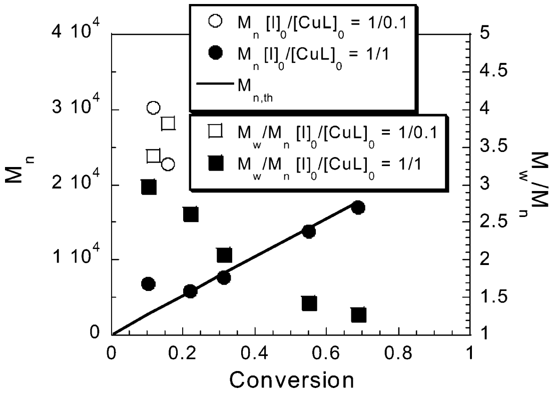


Figure 3. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA using Et_6TREN/CuBr. See Table 1 for polymerization conditions.

distribution was quite narrow, and the polydispersity index eventually reached 1.12. In contrast, rather surprisingly, Et_6TREN/CuBr promoted a much slower and less controlled polymerization under the same conditions (Figures 1 and 3). Monomer conversion was only 16%, even after 4 h, and molecular weight was much higher than that expected for quantitative initiation. The polydispersity of the polymer was quite high (M_w/M_n = 3.82). To increase polymerization rate and improve the degree of control exerted over the polymerization process, catalyst concentration was increased to 100 mol % vs initiator, which is 10 times higher than the original conditions. Even under these higher catalyst concentration conditions, polymerization was still slow, and 69% conversion was observed in 48 h (Table 1). Control over polymerization was improved. Molecular weight increased with conversion and agreed with predicted values, at least after 20% monomer conversion, and the polydispersity index finally reached 1.28 (Figure 3). However, deviation of molecular weight from expected value and high polydispersity index was still observed at low monomer conversion. These results indicate that the low initial concentrations of the Et_6-TREN copper(II) species did not efficiently deactivate the growing radicals, leading to higher molecular weight and broad molecular weight distribution. Control was not fully attained until Cu(II) concentration increased significantly. Thus, bulkiness of the alkyl groups on the nitrogen atoms in a TREN ligand strongly affects all aspects of catalytic performance, both rate and control, in an ATRP polymerization. Especially, the deactivation step is strongly hindered by the presence of bulky alkyl groups.

To confirm the effect of a phenoxy group in a branched tetradentate ligand on the performance of an ATRP catalyst, BA polymerization was investigated under similar conditions using a *N*-tetraethyltriaminephenoxy (Et_4TAPH) copper(I) complex. In this complex one of the (diethylamino)ethylene groups ($-CH_2CH_2NEt_2$) in Et_6-TREN has been replaced by a 2,4-dimethylphenoxymethylene group, ($-CH_2PhO^-$). The catalyst complex was evaluated under conditions that required the presence of 100 mol % catalyst vs initiator. Polymerization was much faster than a Et_6TREN/CuBr-mediated polymerization (Figure 1); however, both large deviation of molecular weight from theoretical values and broad molecular weight distribution were observed, as reported before (Figure 4).[14] The polymerization rate was comparable to that of a Me_6TREN/CuBr-mediated polymerization with 10 mol % catalyst concentration, indicating the Et_4TAPH copper(I) catalyst complex was approximately 10 times less active than Me_6TREN/CuBr. Therefore, one can conclude that phenoxy group provides a positive effect on activity but a strongly negative effect on the deactivation step, leading to poor control over polymerization.

These results on Me_6TREN, Et_6TREN, and Et_4TAPH catalyst-mediated polymerizations provide some insight into steric effects and charged group effects on activity and degree of control over polymerization in branched amine-based catalysts and can be summarized as follows.

1. Activity: Me_6TREN > Et_4TAPH > Et_6TREN. Less bulky alkyl groups on the nitrogen atom lead to higher

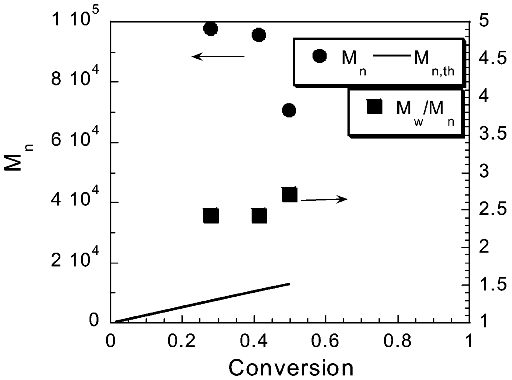


Figure 4. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA using the Et_4TAPH Cu(I) complex. See Table 1 for polymerization conditions.

activity. A charged ligand (phenoxy group) increases activity.

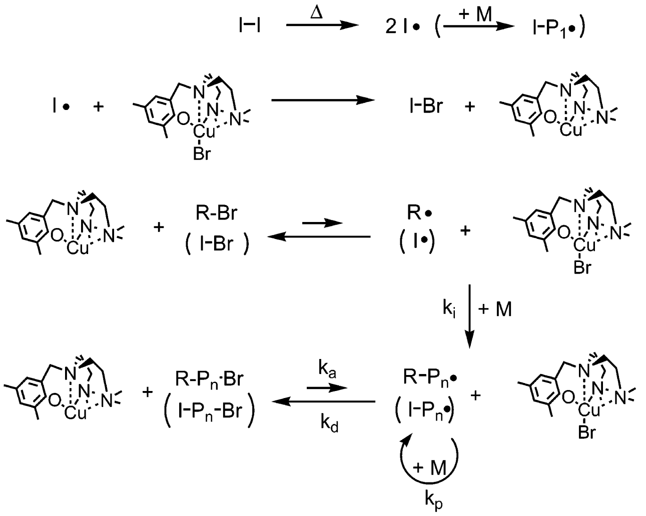
2. Control over polymerization: Me_6TREN > Et_6-TREN > Et_4TAPH. A less bulky group is preferred again. However, in this case, a charged ligand decreases the level of control over polymerization.

These observations suggest that charged ligands having less bulky alkyl group are possible candidates for the formation of catalyst complexes that can promote ATRP with much higher activity, while retaining sufficient degree of control over polymerization.

BA Polymerization with Me_4TAPH Copper Complex. Since the earlier section indicated the potential of preparing a highly active catalyst from a complex consisting of a charged ligand having small alkyl groups as substituents, the *N*-tetramethyl analogue of Et_4-TAPH, *N*-tetramethyltriaminephenoxy (Me_4TAPH) copper complex, was synthesized and investigated as a ligand for formation of a copper complex suitable for use as a catalyst in the ATRP of BA (Scheme 1). The Me_4-TAPH ligand was synthesized using a similar procedure to that employed in the synthesis of the Et_4TAPH, that is, a Mannich reaction of 2,4-dimethylphenol, paraformaldehyde, and *N*,*N*,*N*′,*N*′-tetramethyldiethylenetriamine. The Me_4TAPH ligand was obtained as a yellow oil in 79% yield.

Synthesis of the Me_4TAPH copper(I) complex was initially attempted by lithiation of Me_4TAPH ligand followed by a reaction with CuCl in acetonitrile, which is the same procedure successfully used for Et_4TAPH copper(I) complex synthesis.[14] However, the Me_4TAPH copper(I) complex is quite air sensitive and readily decomposed, even in the Schlenk flask, presumably by an oxidation reaction with trace amounts of oxygen. This fact indicates that the Me_4TAPH copper complex really prefers to exist in a higher oxidation state and hence potentially possesses very high activity for ATRP. Therefore, the more stable copper(II) complex was synthesized through the reaction between the Me_4TAPH lithium salt and $CuBr_2$ and was investigated as an ATRP catalyst in a simultaneous reverse and normal initiation system (SR&NI).[19] The Me_4TAPH copper(II) complex is poorly soluble in nonpolar solvents and highly soluble in polar solvents; therefore, purification of the copper complex has not been successful so far. The crude complex obtained after evaporation of solvent from reaction mixture was used as the catalyst. Quantitative reaction was assumed in order to calculate the copper complex content (Scheme 2).

Scheme 3. Proposed Mechanism for Simultaneous Reverse and Normal Initiation with the Me_4TAPH Copper(II) Complex



The ATRP of BA was investigated using the Me_4-TAPH copper(II) complex as the source of the catalyst employing SR&NI protocol.[19] As reported earlier, SR&NI provides well-controlled acrylate and styrene polymerizations with highly active catalyst systems that can be added to the reaction in the higher, more stable, oxidation state, e.g., Me_6TREN/$CuBr_2$. The proposed mechanism of SR&NI using the Me_4TAPH copper(II) complex is illustrated in Scheme 3. The thermally generated radical ($I^•$) is trapped by the copper(II) species, and then the newly generated copper(I) complex starts and continues the ATRP polymerization with normal initiation and propagation mechanisms. However, in this initiation system, polymerization is initiated not only from usual ATRP initiator (R−X) but also from fragments of the conventional radical initiator (I−X). In this study, methyl 2-bromopropionate (MBP) and 2,2′-azobis(isobutyronitrile) (AIBN) were used as the ATRP initiator and conventional radical initiator, respectively. Taking into account the initiation efficiency of AIBN ($f \sim 0.8$), the theoretical molecular weight was calculated from eq 2:

$$M_{n,th} = (\Delta[M]/([MBP]_0 + (2 \times 0.8[AIBN]_0) \times MW(monomer) + MW(initiator) \quad (2)$$

BA polymerization with SR&NI was conducted with $[BA]_0/[MBP]_0/[AIBN]_0/[Me_4TAPH/Cu(II)]_0 = 200/1/0.062/0.1$ in bulk. 10 mol % Me_4TAPH copper(II) complex vs ATRP initiator was used. The ratio, $[AIBN]_0/[Me_4TAPH/Cu(II)]_0 = 0.62$, was selected as it was expected to lead to complete reduction of the Cu(II) complex to the Cu(I) species based on a decomposition efficiency of 0.8 for AIBN. The results are presented in Table 2 along with results from other experiments. The copper(II) complex dissolved in polymerization media and provided a homogeneous polymerization mixture. First, polymerization was conducted at 60 °C. Interestingly, under these conditions, polymerization did not proceed at all (Figure 5). No monomer conversion was observed even after 8 h. As reported earlier from our group, in a SR&NI ATRP using Me_6TREN/$CuBr_2$ as catalyst precursor under homogeneous conditions, BA polymerization did not occur at 60 °C. This was attributed to the initial Cu(II) concentration being high, and radical

Table 2. Conditions and Results for ATRP of BA with Simultaneous Reverse and Normal Initiation (SR&NI) Using the Me_4TAPH Cu(II) Complex[a]

expt	$[MBP]_0/[Cu(II)]_0$	t (h)	T (°C)	conv (%)	M_n ($\times 10^{-4}$)	$M_{n,theo}$ ($\times 10^{-4}$)	M_w ($\times 10^{-4}$)	M_w/M_n
1	1//0.1	8	60	0				
2	1/0.2	6	90	43.4	1.23	1.03	1.42	1.16
3	1/0.1	3	90	63.5	1.39	1.49	1.71	1.22
4	1/0.05	2	90	76.8	1.80	1.81	2.24	1.25

[a] Polymerization conditions: ATRP initiator = methyl 2-bromopropionate, conventional radical initiator = AIBN, $[BA]_0 = 6.64$ M, $[BA]_0/[MBP]_0/[AIBN]_0 = 200/1/0.062$, BA/anisole = 1/0.05 v/v.

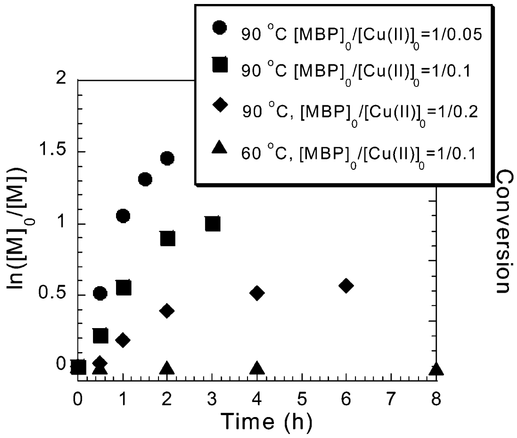


Figure 5. Kinetic plots for the polymerization of BA with simultaneous reverse and normal initiation using the Me_4TAPH Cu(II) complex. See Table 2 for polymerization conditions.

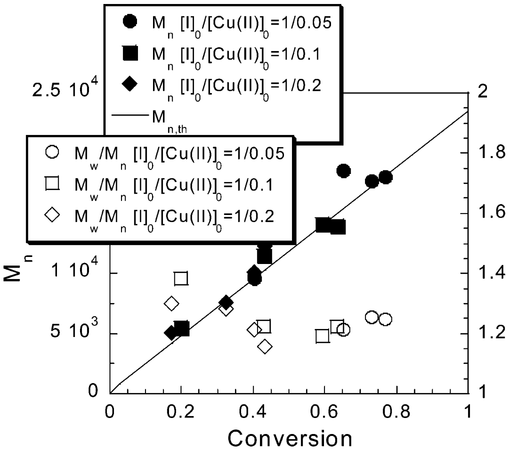


Figure 6. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA with simultaneous reverse and normal initiation using the Me_4TAPH Cu(II) complex. See Table 2 for polymerization conditions.

formation was too slow at this temperature to quickly reduce the complex; hence, a very long induction period was observed.[19] In the Me_4TAPH copper(II) catalyst-based SR&NI system, the polymerization mixture was homogeneous, and the polymerization did not occur at 60 °C for the same reason. Thus, a subsequent polymerization was conducted at an elevated temperature, 90 °C, to increase the rate of thermal decomposition of AIBN. At this temperature, polymerization occurred, and monomer conversion reached 64% in 3 h, although some curvature of kinetic plots was observed. The molecular weight agreed with predicted values during each stage of the polymerization, and the molecular weight distribution was narrow; the polydispersity index eventually reached $M_w/M_n = 1.22$ (Figure 6). To confirm the effect of Cu(II) complex concentration, the initial feed of Cu(II) was changed to 5 and 20 mol % vs ATRP initiator, while other conditions remained fixed. Even in the presence of only 5 mol % Cu(II) complex, the polymerization was still controlled. As expected, the polymerization rate decreased and the molecular weight distribution was getting narrower with increasing Cu(II) concentration. Both observations are due to a higher final concentration of Cu(II) in the reaction medium (Figures 5 and 6). The temperature dependence of polymerization rate and the effect of initial ratio of Cu(II) complex to standard ATRP initiator were similar to the behavior observed in homogeneous SR&NI ATRP with $Me_6TREN/CuBr_2$.

When one compares the rate of polymerization and the level of control over polymerization between complexes formed with Me_4TAPH and Me_6TREN, the polymerization rate and the level of control over polymerization of catalysts formed with Me_4TAPH were respectively slightly slower and slightly lower than those reported previously[19] for the $Me_6TREN/CuBr_2$ system under similar conditions. Thus, the presence of the phenoxy group did not increase the polymerization rate as expected. However, when compared the catalytic performance seen with complexes formed with Et_4TAPH ligands, a remarkable steric effect was again observed. There was a dramatic improvement in both the rate of polymerization and in the level of control. The Me_4TAPH copper complex demonstrated significantly higher activity and better control over polymerization than the Et_4TAPH complex.

BA Polymerization with BPPY Copper Complex. Since pyridine has a sp^2 nitrogen and the carbon atoms on nitrogen can only spread out in two dimensions, a pyridine ligand can potentially provide a less hindered environment for a complexed metal center compared to alkylamine ligand. Although complexes with a pyridine ligand promote slower ATRP polymerization than complexes formed from alkylamine ligands in general, we already reported that a tripodal ligand containing three pyridines, tris[2-(pyridyl)methyl]amine (TPMA), mediated fast and well-controlled acrylate and styrene polymerizations.[9] Therefore, we decided to introduce an anionic charged group into this tripodal pyridine ligand. In this study, one neutral pyridine group was replaced with an anionic pyrrolide group, so that a charge was located on nitrogen atom.

Routes for synthesis of the ligand and complex are shown in Scheme 2. The *N*,*N*-bis[(2-pyridyl)methyl-2-aminomethylpyrrole (BPPY) ligand was synthesized through a three-step reaction. The corresponding copper(I) neutral complex was synthesized through the usual procedure; lithiation of the ligand followed by reaction with CuCl in acetonitrile and was obtained as deep red solid. The resulting copper(I) complex possessed limited solubility in acetonitrile and precipitated from the reaction mixture as a deep red solid. This complex has poor solubility even in DMF. One possible reason for the low solubility is the formation of a multinuclear complex formed by bridging through the

Table 3. Conditions and Results for ATRP of BA Using the BPPY Cu(I) Complex[a]

expt	catalyst	BA/DMF (v/v) (DMF vol %)	t (h)	conv (%)	M_n ($\times10^{-4}$)	$M_{n,theo}$ ($\times10^{-4}$)	M_w ($\times10^{-4}$)	M_w/M_n
1	BPPY Cu(I)	0/0 (0 vol %)	8	23.2	1.03	0.61	1.63	1.57
2	BPPY Cu(I)	1/0.1 (9 vol %)	2.2	57.0	1.38	1.35	2.13	1.54
3	BPPY Cu(I)	1/0.33 (25 vol %)	2	78.4	1.55	2.03	2.16	1.39
4	BPPY Cu(I)	1/0.67 (40 vol %)	2	88.8	1.69	2.29	2.42	1.43
5	$Me_6TREN/CuBr$	1/0.67 (40 vol %)	4	62.0	1.22	1.61	1.52	1.24

[a] Polymerization conditions: initiator = methyl 2-bromopropionate, $[BA]_0/[MBP]_0/[Cu(I)/L]_0 = 200/1/0.1$; for expt 1, $[BA]_0 = 6.64$ M, solvent = anisole, BA/anisole = 1/0.05 v/v; for expt 2, $[BA]_0 = 6.34$ M; for expt 3, $[BA]_0 = 5.23$ M; for expt 4 and 5, $[BA]_0 = 4.19$ M.

Table 4. Conditions and Results for ATRP of BA Using the BPPY Cu(I) Complex in the Absence and Presence of Cu(II) Deactivator[a]

expt	Cu(II) complex	t (h)	conv (%)	M_n ($\times10^{-4}$)	$M_{n,theo}$ ($\times10^{-4}$)	M_w ($\times10^{-4}$)	M_w/M_n
1		2	88.8	1.69	2.29	2.42	1.43
2	$CuBr_2$	3	86.0	1.71	2.22	2.58	1.51
3	$Me_6TREN/CuBr_2$	2	88.8	1.55	2.29	2.26	1.46

[a] Polymerization conditions: initiator = methyl 2-bromopropionate, temperature = 60 °C, Cu(II) complexes were added as a stock solutions in DMF. Concentration of Cu(II) in stock solution was 11.2 μM ($CuBr_2/Me_6TREN = 1/1$ mol/mol), $[BA]_0 = 4.19$ M, BA/DMF = 3/2 w/w; for expt 1, $[BA]_0/[I]_0/[Cu(I)\ complex]_0 = 200/1/0.1/$, for expt 2 and 3, $[BA]_0/[I]_0/[Cu(I)\ complex]_0/[Cu(II)\ complex]_0 = 200/1/0.1/0.003$.

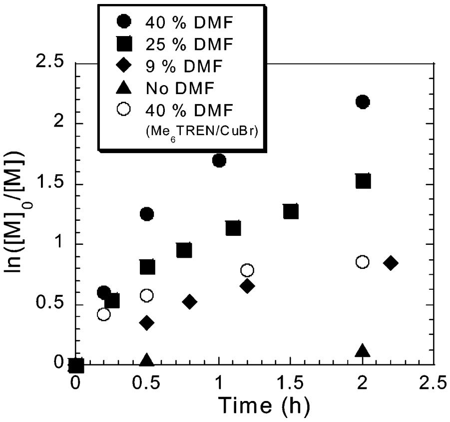


Figure 7. Kinetic plots for the polymerization of BA using the BPPY Cu(I) complex. See Table 3 for polymerization conditions.

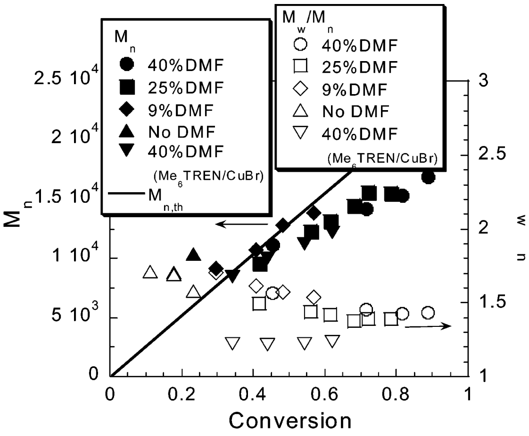


Figure 8. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA using the BPPY Cu(I) complex. See Table 3 for polymerization conditions.

ligand due to too low steric hindrance around metal. In contrast to the Me_4TAPH copper(I) complex, the BPPY copper(I) complex was relatively stable to air and moisture. Therefore, the catalytic performance was evaluated using the copper(I) complex in normal ATRP-initiated BA polymerization, although the complex was not fully characterized due to its low solubility. The results are summarized in Table 3.

Polymerization was conducted in the presence of 10 mol % catalyst vs initiator at 60 °C. When the polymerization was performed in bulk, the catalyst did not completely dissolve in the polymerization mixture, and a relatively slow and poorly controlled polymerization was observed (Figures 7 and 8). This was presumably due to low solubility of copper complex providing too low catalyst concentration in the solution. To improve the solubility of the copper catalyst, DMF was used as a solvent. At least 40 vol % of DMF vs monomer was necessary to completely dissolve the copper complex. As shown in Figure 7, polymerization rate increased with increasing amounts of DMF because the effective catalyst concentration in polymerization mixture was increased. When BA polymerization was conducted using $Me_6TREN/CuBr$ in the presence of 40 vol % DMF, a much slower rate of polymerization was observed. Thus, use of a pyrrolide ligand fundamentally affects the K_{ATRP} and enhances the polymerization activity. Regarding control over polymerization, the molecular weight increased with conversion, but some deviation from predicted values was observed at high conversion, suggesting increased contributions from chain transfer reactions. Molecular weight distributions are fairly narrow, although broader than with catalysts based on Me_6TREN, indicating that the presence of the anionic pyrrolide group increases the rate constant of activation, k_a, but does not significantly increase the rate constant of deactivation, k_d, as observed in other charged ligand catalyst systems.

To confirm this hypothesis and to improve the level of control over polymerization, 3 mol % of $Me_6TREN/CuBr_2$ or $CuBr_2$ vs BPPY copper(I) complex was added as an additional deactivator. It was anticipated that the presence of the efficient deactivator would improve the level of control over the reaction, as had been reported before with the Et_4TAPH copper complex.[14] The results are shown in Table 4. The addition of deactivators did not improve the degree of control over polymerization. This may indicate that the overall activity of the BPPY-based catalyst complex is already higher than that of the Me_6TREN copper complex which remains in its lower oxidation state.Hence, inclusion of an anionic pyrrolide group in a tripodal ligand led to formation of a catalyst system that displayed an increase of the polymerization rate but reduced control over polymerization.

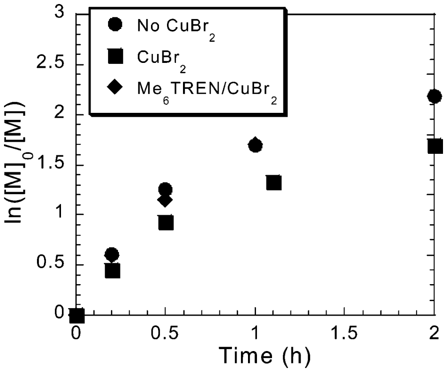


Figure 9. Kinetic plots for the polymerization of BA using the BPPY Cu(I) complex in the presence of Cu(II) deactivator. See Table 4 for polymerization conditions.

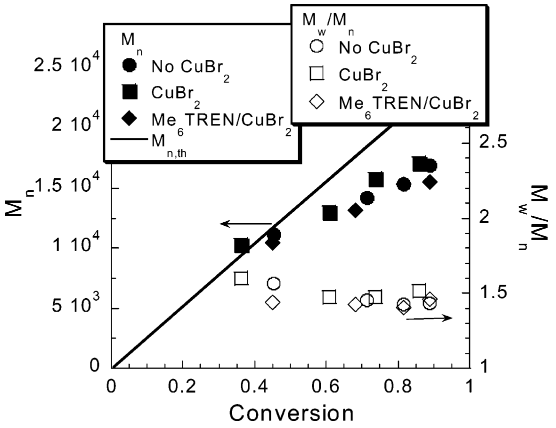


Figure 10. Evolution of M_n and M_w/M_n vs conversion for the polymerization of BA using BPPY Cu(I) complex in the presence of Cu(II) deactivator. See Table 4 for polymerization conditions.

Conclusions

Catalyst complexes formed with newly synthesized neutral Et$_6$TREN, anionic Me$_4$TAPH, and anionic BPPY ligands were investigated for copper-mediated ATRP. Several guidelines for development of new ATRP catalysts can be suggested after comparison of activity and level of control over polymerization using these complexes, and complexes formed with Me$_6$TREN and Et$_4$-TAPH, for BA polymerization.

Steric hindrance around the copper metal strongly affects both activity and control over polymerization as indicated by a comparison of Me$_6$TREN- and Me$_4$TAPH-mediated BA polymerization, with Et$_6$TREN- and Et$_4$-TAPH-mediated BA polymerization. Polymerizations conducted with more sterically hindered *N*-ethyl-substituted ligands promoted much slower and poorly controlled BA polymerization compared to *N*-methyl analogues, for both neutral and anionic ligand catalyst systems. Reducing steric hindrance around the metal center could be an important factor for the future development of highly active catalysts.

The introduction of an anionic group into a ligand decreases the deactivation rate and reduces control over polymerization. Thus, the BPPY copper complex has a much higher activity as compared to that of a complex with a neutral ligand TPMA. Copper complexes with charged ligands remain potential candidates for high-performance ATRP catalysts after continued fine-tuning of ligand structure.

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