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Ethanol-Mediated Living Radical Homo- and Copolymerizations with Cp*-Ruthenium Catalysts: Active, Robust, and Universal for Functionalized Methacrylates

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ABSTRACT: With judiciously selected ligands (phosphines) and cocatalysts (amines), a series of highly active and functionality-tolerant pentamethylcyclopentadienyl (Cp*) ruthenium catalysts [Cp*Ru(Cl)L^1L^2; L^1 and L^2: ligands] have been developed for living radical homo- and copolymerizations universally accessible to a variety of functional methacrylates in ethanol and related alcoholic and polar media. In particular, the ligand/cocatalyst combination of tri-*m*-tolylphosphine [P(*m*Tol)$_3$; *m*Tol = *m*-MeC_6H_5] and a hydrophilic amine, 2-dimethylamino-1-ethanol [$Me_2N(CH_2)_2OH$; 2-DMAE], led to a very active and robust catalyst that induced fast polymerizations and fine molecular-weight control (M_w/M_n < 1.2) *in ethanol* for not only homopolymerizations but also random or block copolymerizations with pendent-functional methacrylates carrying poly(ethylene glycol) (−PEG), dimethylamino [$-N(CH_3)_2$], and hydroxyl (−OH) groups. The accessible solvents included a wide variety of alcohols (methanol, ethanol, etc.), environmentally benign and readily recoverable, in which high reaction rate and solution homogeneity readily were attained for the polar monomers. ^{31}P NMR analysis on the catalyst/cocatalyst systems revealed that a part of the starting coordinatively saturated 18e complex Cp*Ru(Cl)[P(*m*Tol)$_3$]$_2$ is dynamically transformed in situ into an amine-coordinated analogue Cp*Ru(Cl)[P(*m*Tol)$_3$](2-DMAE), and this dynamic ligand−cocatalyst exchange may in turn generate a transient unsaturated 16e form Cp*Ru(Cl)[P(*m*Tol)$_3$] that may be the "real" active catalyst. The products thus included homopolymers, AB- and ABC-block copolymers, and random/statistical copolymers; the last could be extended to as many as six functional comonomers, while retaining compositional uniformity and narrow molecular weight distributions independent of monomer conversion.

Introduction

Functional polymeric materials are hardly homopolymers but instead copolymers, with some combination of functionality required for higher performances often in random or statistical distribution along the backbone. Accordingly, radical polymerization has extensively been applied for the preparation of functional polymers because of the following advantages over the ionic and the coordination counterparts: a wide variety of applicable monomers, their high crossover reactivity in copolymerization, and a tolerance to functionalities (free from pendent group protection/deprotection). Polymer functions can be tuned by monomer combination, comonomer feeding ratio, and perhaps, most important, the placement (or sequence) of functional groups such as statistical, gradient, block, graft, and so on. A large number of "random" copolymers can indeed be obtained by conventional "free" radical polymerization, but therein not only the molecular weight (chain length) but also the compositional distribution cannot be controlled because of irreversible termination and chain-transfer reactions, where the monomer composition in feed continuously changes as the reaction proceeds. The composition of the resulting copolymers accordingly varies with conversion and so does with the polymer chain length. Thus, the final products are usually an ill-defined mixture, or a blend, of copolymers of varying composition and molecular weight, and such a nonuniformity is undesirable for advanced functional (co)polymers.

Living radical polymerization is now a powerful tool to control the primary structures of polymers (e.g., molecular weight, its distribution, and terminal structures) into well-defined architectures (e.g., block, graft, and star) even with functional monomers.[1−3] Another important advantage, though possibly less recognized, of living random copolymerization is that the compositional distribution is essentially uniform in a set of copolymers within a single product. In this viewpoint, a system applicable to a variety of functionalities, e.g., hydrophobic/hydrophilic, acidic/basic, cationic/anionic, rigid/soft, etc., for living copolymerization would be valuable to prepare "uniform" copolymer chains with narrow distributions for both molecular weight and composition. To this end, a universal catalyst system and a universal copolymerization thereby for a variety of functional monomers are fundamentally required in the precision syntheses of block, random (statistical), and other copolymers where functionalities are placed in desired positions and sequences.

Metal-catalyzed living radical polymerization (Scheme 1) is one of such precision controlled processes, where a transition metal complex catalyzes a reversible activation of carbon−halogen bond to give a reduced instantaneous concentration of the growing radical species for the suppression of side reactions,[1,2] to offer such advantages as a high initiating efficiency, an excellent controllability, and above all a wide applicability (versatility) for monomers over ionic and other living polymerizations.

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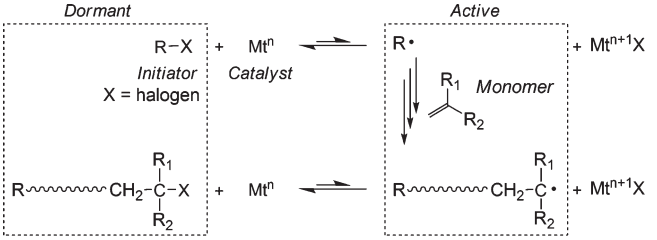
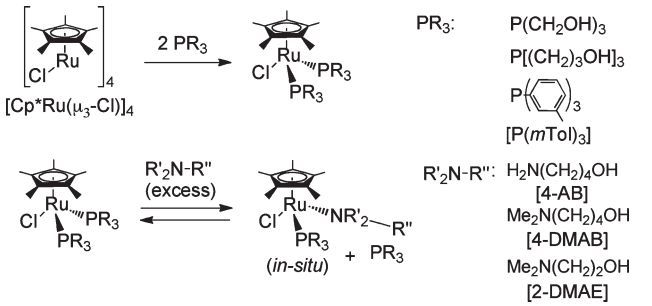
Scheme 1. Transition-Metal-Catalyzed Living Radical Polymerization



Scheme 2. Preparation of Cp*RuCl(PR$_3$)$_2$ from [Cp*Ru(μ_3-Cl)]$_4$ and in-Situ Ligand Exchange with an Amine Cocatalyst



On the other hand, the use of transition metal catalysts, in turn, often incurs disadvantages as well: the products contamination by metal residues and the catalyst poisoning (deactivation or decomposition) by polar and coordinative functionality that limits the range of available monomers and solvents. Despite the current progresses in catalysts activity and functionality tolerance via elaborate design of metal complexes, there have been only sporadic examples of highly versatile or "universal" metal-catalyzed living radical copolymerizations of polar functional monomers into well-defined "uniform" functional copolymers. This is likely due to the fact that catalysts are more or less specific for specific monomers, namely, the difficulty in devising "universal" systems for various monomers with different functional moieties and reactivity in terms of catalyst, solvent, temperature, etc.

This work is to extend our continuing design of pentamethylcyclopentadiene (Cp*) ruthenium complexes toward universal catalysts for functional monomers (Scheme 2), on the basis of our recent finding that Cp*-ruthenium complexes are readily tunable from a useful tetrameric precursor [Cp*Ru(μ_3-Cl)]$_4$ by combinations of phosphine ligands and amine cocatalysts, for a faster polymerization, a higher activity (reduction of dosage), and an effective removability.[4] The ligand/cocatalyst combination of tri-*m*-tolylphosphine [P(*m*Tol)$_3$; *m*Tol = *m*-MeC$_6$H$_5$] and a hydrophilic amine, 2-dimethylamino-1-ethanol [Me$_2$N(CH$_2$)$_2$OH; 2-DMAE], allowed high-caliber control over not only homopolymerizations but also block and random copolymerizations of functionalized methacrylates carrying polar pendent groups, poly(ethylene glycol) (−PEG), dimethylamino [−N(CH$_3$)$_2$], and hydroxy (−OH). The system was indeed so versatile and universal in ethanol as to catalyze, for example, a homogeneous living random copolymerization of as many as six monomers of widely varying structure and polarity, in which all the monomers are polymerized at virtually the same rates into statistical copolymers of controlled molecular weights and very narrow molecular weight distribution (MWD).

Experimental Section

Materials. Poly(ethylene glycol) methacrylate [PEGMA; CH$_2$=CMeCO$_2$(CH$_2$CH$_2$O)$_n$Me; n = 8.5 on average] (Aldrich), *N,N′*-dimethylaminoethyl methacrylate (DMAEMA) (TCI; >98%), dodecyl methacrylate (DMA) (TCI; >95%), and benzyl methacrylate (BzMA) (TCI; >98%) were purified by passing through an inhibitor removal column (Aldrich) and were subsequently degassed by triple vacuum−argon bubbling cycles before use. 2-Hydroxyethyl methacrylate (HEMA) (Aldrich; >99%) was distilled under reduced pressure before use. Methyl methacrylate (MMA) (TCI; >99%) was dried overnight over calcium chloride and purified by double distillation from calcium hydride before use. All phosphime ligands and materials for the preparation of ruthenium complexes were used as received without further purification and handled in a glovebox (M. Braun Labmaster 130) under a moisture- and oxygen-free argon atmosphere (H$_2$O <1 ppm; O$_2$ <1 ppm): tri-*m*-tolylphosphine [P(*m*Tol)$_3$; Strem; >98%], tris(hydroxymethyl)phosphine (Strem; >85%), tris(3-hydroxypropyl)phosphine (Strem; >80%), ruthenium(III) chrolide hydrate (Wako; >99.9%), 1,2,3,4,5-pentamethylcyclopentadiene (Strem; 98%), and lithium triethyl hydridoborate (Aldrich, 1.0 M solution in THF). Ruthenium tetramer [Cp*Ru(μ_3-Cl)]$_4$[5] and initiator H-(MMA)$_2$-Cl[6] were prepared according to the literature. Toluene and THF (both Kishida Kagaku; purity >99%) were dried and purified by passing through purification columns (Solvent Dispensing System; Glass Contour) and bubbled with dry nitrogen for more than 15 min immediately before use. Ethanol (99.5%), methanol, 2-propanol, and 1-butanol (all from Wako; dehydrated) were bubbled with dry nitrogen for more than 15 min immediately before use. All amine compounds (all from TCI) were similarly degassed before use: 2-DMAE (>99%), 4-amino-1-butanol (>98%), 4-dimethylamino-1-butanol (>98%).

Polymerization Procedures in Ethanol. Polymerization was carried out by the syringe technique under dry argon in baked glass tubes equipped with a three-way stopcock or in sealed glass vials. Typical procedures for the polymerization of PEGMA with the H-(MMA)$_2$-Cl/[RuCp*(μ_3-Cl)]$_4$/P(*m*Tol)$_3$/2-DMAE system are given: In a 50 mL round-bottom flask were placed [RuCp*(μ_3-Cl)]$_4$ (4.3 mg, 0.008 mmol), P(*m*Tol)$_3$ (9.7 mg, 0.032 mmol), and toluene (2 mL). The solution was heated to 60 °C for 12 h, during which period the color changed from black-brown to red-brown, indicative that the phosphine was ligated onto the ruthenium center with dissociation of the tetramer. The homogeneous mixture was cooled to room temperature, evaporated to dryness, and dried further in vacuo for an additional 2 h at room temperature to give brownish powdery products {Cp*RuCl-[P(*m*Tol)$_3$]$_2$}. The flask was then filled with dry argon, to which were added, sequentially, ethanol (5.99 mL), PEGMA (1.76 mL, 4.0 mM), an ethanol solution of 2-DMAE (0.16 mL, 500 mM), and an ethanol solution of H-(MMA)$_2$-Cl (0.091 mL, 437.4 mM, 0.40 mmol) under dry argon at room temperature; the total volume of the reaction mixture was thus 8.0 mL. Immediately after mixing, aliquots (0.50−1.0 mL each) of the solution were distributed with a syringe into glass tubes that were then sealed (except when a stopcock was used) and placed in an oil bath kept at desired temperature. In predetermined intervals, the polymerization was terminated by cooling the reaction mixtures to −78 °C. Monomer conversion was determined by directly monitoring the reaction solutions by ^{1}H NMR (DMSO-d_6) on the basis of the integrated peak areas of the residual PEGMA vinyl protons [CH_2=CMe−] at 5.7−6.0 ppm relative to the pendent ester methylenes [−C(=O)−OCH_2−] in both monomer and the polymer at 3.8−4.2 ppm. The quenched reaction solutions were evaporated to dryness to give the products that were subsequently dried overnight under vacuum at room temperature.

Monomer conversion of each methacrylate was determined by ^{1}H NMR (DMSO-d_6) even for copolymerizations with separable peaks derived from monomers and an ethanol peak at 3.21 ppm as internal standard. For example, in hexa-random copolymerization of PEGMA, HEMA, DMAEMA, MMA DMA, and BzMA, peaks from one of vinyl protons at around

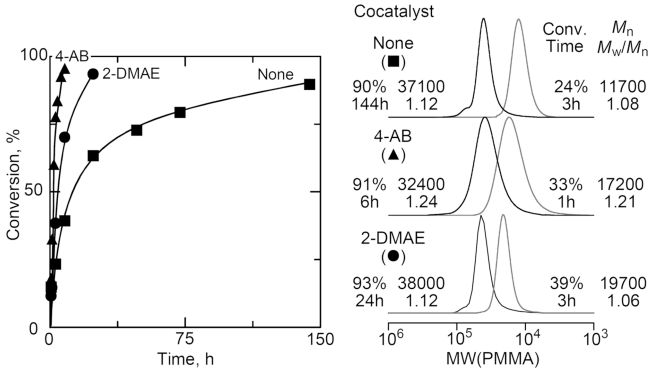


Figure 1. Effects of amine cocatalysts on the polymerization of PEGMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE in ethanol at 40 °C: [PEGMA]$_0$ = 0.5 M; [H-(MMA)$_2$-Cl]$_0$ = 5.0 mM; [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.5 mM; [P(mTol)$_3$]$_0$ = 4.0 mM; [amine]$_0$ = 0 or 10 mM. Amine: 4-AB (▲); 2-DMAE (●); none (■).

6 ppm were separately observed except for PEGMA and DMAEMA (overlapped at 5.978 ppm). For the two methacrylates, peaks from the pendent ester methylenes (4.00−4.20 ppm) were detected at different positions. The peak positions for the characterization are as below: 6.033 ppm (BzMA); 6.024 ppm (DMA), 5.994 ppm (HEMA), 5.966 ppm (MMA), 4.05−4.08 ppm (PEGMA), 4.01−4.05 (DMAEMA).

Measurements. The MWD, M_w, and M_w/M_n ratios of the polymers were measured by size-exclusion chromatography (SEC) in DMF at 40 °C on three polystyrene gel columns [Shodex KF-805 L (pore size: 2−100 nm; 8.0 mm i.d. × 30 cm); flow rate, 1.0 mL/min] connected to a Jasco PU-980 precision pump and a 930-RI refractive index detector, and a 970-UV ultraviolet detector. The columns were calibrated against 13 standard poly(MMA) samples (Polymer Laboratories; M_n = 630−1 200 000; M_w/M_n = 1.06−1.22) as well as the monomer. ^{31}P NMR spectra of the ruthenium complexes were measured with $(C_2H_5O)_2POH$ (12 ppm) as an internal standard on a JEOL JNM-LA500 spectrometer operating at 500.16 MHz at room temperature.

Results and Discussion

Living Polymerization of PEGMA. We have recently reported[4] that $NH_2(CH_2)_4OH$ (4-AB) is an effective cocatalyst that accelerates the living radical polymerization of MMA in toluene with Cp*RuCl[P(mTol)$_3$]$_2$, prepared in situ from [Cp*Ru(μ_3-Cl)]$_4$ and P(m-Tol)$_3$.[7] According to direct ^{31}P NMR analysis, the added amine is concluded to undergo in-situ ligand exchange with one of the phophines to give a phosphine-amine−ruthenium complex that in turn works as an active catalyst. With the aminoalcohol ligation, the in-situ generated complex was rather hydrophilic, as demonstrated by the quantitative removal of its residue upon washing as-polymerized reaction mixtures with water.

The in-situ formation of the active and hydrophilic catalyst encouraged us to apply it for the polymerization of PEGMA, a representative functional methacrylate with a polyether pendent chain. Ethanol was employed as an environmentally benign solvent that also ensures the solubility for a wide range of functional polymers. Crucial is whether this catalyst system withstands the possible poisoning and deactivation by the polyether pendant and/or the alcohol solvent.

Thus, PEGMA was polymerized with the Cp*RuCl[P(mTol)$_3$]$_2$/4-AB system in conjunction with H-(MMA)$_2$-Cl (initiator) in ethanol at 40 °C (Figure 1). Despite the low temperature, the monomer was rapidly consumed (91% conversion in 6 h), and the rate with the added amine was much greater than in its absence (90% in 144 h). The SEC curves of the obtained polymers showed narrow MWDs (M_w/M_n = 1.2−1.3), and the peaks shifted to higher molecular weight with increasing conversion, while keeping the narrow distributions. However, the final MWDs were a little broader than those without the amine cocatalyst, probably due to too high an activity of the amine-activated complex.

Table 1. Polymerizations of PEGMA in Various Solvents at 40 °C[a]

solvent	ε_r[b]	time (h)	conv (%)	M_n	M_w/M_n
MeOH	32.7	1	23	14 300	1.25
		8	90	33 300	1.29
EtOH	23.8	3	39	19 700	1.06
		24	93	38 000	1.12
2-ProOH	18.3	3	27	11 100	1.09
		30	96	32 600	1.16
1-BuOH	17.1	3	37	16 700	1.11
		24	98	38 700	1.16
THF	7.6	10	26	10 400	1.08
		72	87	30 900	1.15
toluene	2.4	6	25	15 000	1.06
		96	89	39 300	1.11

[a] [PEGMA]$_0$ = 500 mM; [H-(MMA)-Cl]$_0$ = 5.0 mM; [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.50 mM; [P(mTol)$_3$]$_0$ = 4.0 mM; [2-DMAE]$_0$ = 10 mM. [b] ε_r: relative dielectric constant.[9]

To modulate catalytic activity, a bulky tertiary amino alcohol (2-DMAE) was employed in place of primary 4-AB because we already know that the catalytic activity with a tertiary amine cocatalyst is milder than with a primary amine. As expected, the polymerization was a little slower (93% in 24 h), but the MWD became as narrow as those for the amine-free systems (M_w/M_n = 1.06−1.12). Therefore, a tertiary amino alcohol proved to be an excellent cocatalyst for Cp*RuCl[P(mTol)$_3$]$_2$ that enables both rate enhancement and the precision control of polymer molecular weight and MWD. The results also confirmed that the in-situ formed catalyst tolerates the polar and possibly ligating polyether and alcohol.

Effects of Solvents. In metal-catalyzed living radical polymerization, solvent polarity often affects catalytic activity.[8] The PEGMA polymerization with the Cp*RuCl[P(mTol)$_3$]$_2$/2-DMAE catalytic system was therefore examined in a series of polar solvents that well dissolve PEG-rich polymers. Table 1 shows the results for five polar solvents [methanol (MeOH), ethanol (EtOH), 2-propanol (2-PrOH), 1-buthanol (1-BuOH), and THF] along with toluene. Regardless of their difference in polarity and structure, all the solvents employed led to fast, homogeneous, and finely controlled reactions: monomer conversion reached ca. 90% or above; and the products MWD was invariably narrow (M_w/M_n = 1.1−1.2). However, polymerization rate was obviously dependent on the solvents: the higher the polarity, the lower the rate. Also, methanol gave the fastest polymerization but slightly broader MWDs (M_w/M_n > 1.2) than the others (M_w/M_n ∼ 1.1).

^{31}P NMR Analysis of the in-Situ Forming Ru Complexes. To further examine these solvent effects, Cp*RuCl[P(mTol)$_3$]$_2$ was analyzed by ^{31}P NMR spectroscopy in situ in three solvents (toluene, ethanol, and methanol) (Figure 2). In nonpolar toluene solvent (Figure 2A), only a single peak was observed (45 ppm, **a**), most likely derived from the geminally coordinating two equivalent phosphines; no "free" P(mTol)$_3$ (expected at ∼0 ppm) was detected, indicating the quantitative formation of Cp*RuCl[P(mTol)$_3$]$_2$ from [Cp*Ru(μ_3-Cl)]$_4$ and P(mTol)$_3$.

In ethanol and methanol (Figure 2, B and C, respectively), on the other hand, a small peak at upper field (44 ppm, **b**) and a "free" phosphine peak (0 ppm; **c**) were additionally observed along with the double-ligating phosphine peak (**a**). The intensity ratio (**b**/**c**) of peaks **b** and **c** was nearly the same

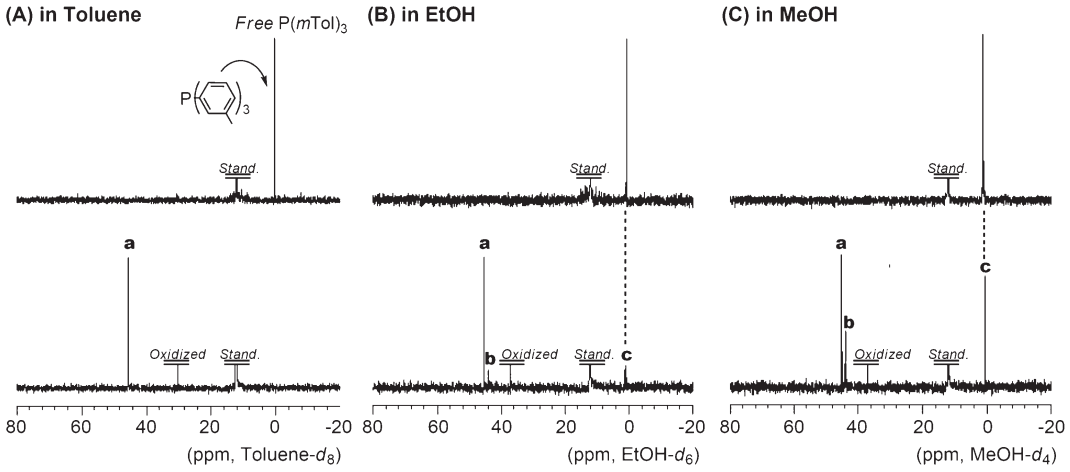
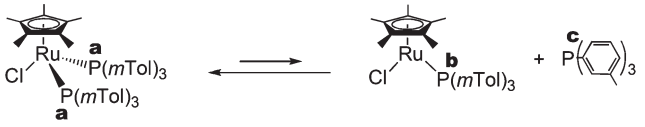


Figure 2. ^{31}P NMR (40 °C) spectra of P(*m*Tol)$_3$ (upper) and Cp*RuCl[P(*m*Tol)$_3$]$_2$ (lower) at 40 °C in three solvents: (A) toluene-d_8; (B) ethanol-d_6; (C) methanol-d_4; internal standard, $(C_2H_5O)_2POH$ in toluene-d_8 sealed in a glass capillary. The complex was prepared in situ under dry nitrogen by mixing [Cp*Ru(μ_3-Cl)]$_4$ and P(*m*Tol)$_3$ (0.50/4.0 mM) in toluene at 80 °C for 12 h, followed by evapolation of toluene and addition of the respective solvent, before transferred into an NMR tube.

Scheme 3. Ligand Release from Cp*RuCl[P(*m*Tol)$_3$]$_2$



in the two alcohols, while both peaks increased relative to peak **a** in methanol. The simultaneous observation of peaks **b** and **c** indicates that the former is most likely derived from a mono-ligating phosphine via ligand elimination (Scheme 3). The spectral results therefore show that phosphine coordination is more or less static in nonpolar toluene solvent, retaining a double ligation, whereas more dynamic in polar alcoholic solvents, leading to equilibrating mixtures of single- and double-phosphine complexes.

Cp*RuCl[P(*m*Tol)$_3$]$_2$ is coordinatively saturated (18e), and for abstracting a halogen from dormant species, one phosphine ligand needs to be eliminated to form a coordinatively unsaturated 16e complex, Cp*RuClP(*m*Tol)$_3$ (Scheme 3). As analyzed by ^{31}P NMR, this in fact happens in polar solvents such as alcohols. The ligand elimination is dynamic with the saturated complex (also fast relative to the ^{31}P NMR time scale), and a moderate balance between the two complexes would be important to achieve an active catalysis (fast polymerization) and a fine molecular weight control (narrow MWD). As also indicated in Figure 2B,C, the 16e complex is more dominant in methanol than in ethanol, and in the former, as a result, the ratio (or concentration) of the unsaturated complex is too high, leading to the faster but less controlled polymerization (cf. Figure 1). Thus, solvent polarity was found to influence polymerization behavior via the formation of the coordinatively unsaturated 16e complex (or ligand elimination). Such solvent effects might be particular to the catalytic systems with coordinatively saturated ruthenium catalysts, different from copper-based (ATRP), where an affinity of the catalyst for halide anions is essential for the catalysis.[10]

Catalyst Systems Optimization via Design of Ligands and Cocatalysts. The observed fine control in the ethanol-mediated PEGMA polymerization with Cp*-ruthenium catalytic system prompted us to further examine various combinations of ligands and cocatalysts toward versatile Cp*Ru-based catalyst systems toward versatility in terms of functional monomers, specifically 2-hydroxyethyl methacrylate (HEMA) and *N*,*N*′-dimethylaminoethyl methacrylate (DMAEMA). The ligands included three alkyl and aryl phosphines: tris(hydroxypropyl)phosphine {P[(CH$_2$)$_3$OH]$_3$}, tris(hydroxymethyl)phosphine [P(CH$_2$OH)$_3$], and P(*m*Tol)$_3$; 4-AB and 2-DMAE were employed as cocatalysts. Table 2 and Figure 3 summarize the results (see also Figure 1 for comparison with PEGMA).

For these three monomers, in short, the combination of P(*m*Tol)$_3$ and 2-DMAE was found to be the best for practically fast reactions of fine control completing within 12−24 h (Figure 3; Table 2, entries 8, 11, and 14). Number-average molecular weight (M_n) increased virtually in direct proportion to monomer conversion, and SEC curves shifted to higher molecular weight, while keeping the quite narrow distributions ($M_w/M_n < 1.2$). A more detailed discussion on system optimization follows.

For HEMA, a hydrophilic alkylphosphine {P[(CH$_2$)$_3$OH]$_3$} with 2-DMAE (10 mM) also gave fairly good results ($M_w/M_n \sim 1.25$) at 40 °C, though with slightly broader MWDs than with more hydrophobic aryl ligand [P(*m*Tol)$_3$] (Table 2, entries 1 and 2). Another hydrophilic alkylphosphine [P(CH$_2$OH)$_3$] resulted in a faster polymerization but broader MWDs ($M_w/M_n = 1.47$) (Table 2, entry 3).

It should be noted that the best results for this monomer with P(*m*Tol)$_3$ were obtained at a lower temperature (25 °C) and at a higher cocatalyst concentration (100 mM) (entry 8). At 40 °C, the polymerizations with 10 mM 2-DMAE and in its absence were gradually retarded and leveled off at ca. 50% conversion, despite narrow MWDs ($M_w/M_n < 1.2$) (entries 4 and 5); a 10 times increase of cocatalyst dose in fact facilitated monomer consumption but also broadened MWD (89% in 13 h; $M_w/M_n = 1.28$) (entry 6). Similar results were obtained with 100 mM 4-AB as a cocatalyst (entry 7).

The lower temperature and the higher cocatalyst concentration needed for HEMA would be attributed to its higher reactivity [e.g., k_p (M^{-1} s^{-1}, 60 °C): 3300 (HEMA); 820 (MMA)].[11] Note, however, that such a difference of the condition for more desirable catalysis is not so serious for copolymerizations under the same conditions as shown later.

For polymerization of DMAEMA, hydrophilic and alkyl cocatalyst P[(CH$_2$)$_3$OH]$_3$ was less suitable than the hydrophobic and aryl counterpart P(*m*Tol)$_3$, the latter giving quite narrow MWDs ($M_w/M_n < 1.1$) (entry 9 vs 11). Importantly, no amine cocatalyst was required for control because of the amino functionality in the monomer (entry 10) to give results very similar to those with 2-DMAE (entry 11).

Table 2. Polymerizations of HEMA, DMAEMA, and PEGMA in Ethanol at 40 °C[a]

entry	monomer	ligand	cocatalyst	[cocat.]$_0$ (mM)	time (h)	conv (%)	M_n[b]	M_w/M_n[b]
1	HEMA[c]	P[(CH$_2$)$_3$OH]$_3$	none	0	144	76	20 900	1.25
2		P[(CH$_2$)$_3$OH]$_3$	2-DMAE	10	72	79	17 200	1.24
3		P(CH$_2$OH)$_3$	2-DMAE	10	13	85	22 700	1.47
4		P(mTol)$_3$	none	0	24	52	17 400	1.12
5		P(mTol)$_3$	2-DMAE	10	24	59	20 500	1.18
6		P(mTol)$_3$	2-DMAE	100	13	89	27 900	1.28
7		P(mTol)$_3$	4-AB	100	4	91	31 500	1.31
8[f]		P(mTol)$_3$	2-DMAE	100	12	88	20 400	1.13
9	DMAEMA[d]	P[(CH$_2$)$_3$OH]$_3$	2-DMAE	10	8	72	8 900	1.91
10		P(mTol)$_3$	none	0	24	85	7 600	1.10
11		P(mTol)$_3$	2-DMAE	10	24	88	8 500	1.08
12	PEGMA[e]	P[(CH$_2$)$_3$OH]$_3$	2-DMAE	10	6	78	47 300	1.51
13[g]		P(mTol)$_3$	none	0	144	90	37 100	1.12
14[g]		P(mTol)$_3$	2-DMAE	10	24	93	38 000	1.12
15[g]		P(mTol)$_3$	4-AB	10	6	91	32 400	1.24

[a] [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.50 mM; [ligand]$_0$ = 4.0 mM. [b] By size-exclusion chromatography calibrated with PMMA standards. [c] [HEMA]$_0$ = 2.0 M; [H-(MMA)-Cl]$_0$ = 20 mM. [d] [DMAEMA]$_0$ = 2.0 M; [H-(MMA)-Cl]$_0$ = 20 mM. [e] [PEGMA]$_0$ = 500 mM; [H-(MMA)-Cl]$_0$ = 5.0 mM. [f] At 25 °C. [g] The same data set as in Figure 1.

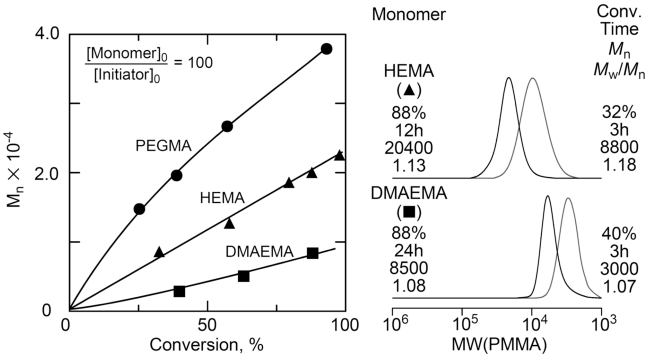


Figure 3. Conversion−M_n plots and SEC curves for the homopolymerizations of PEGMA, HEMA, and DMAEMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE in ethanol at 40 °C (PEGMA, DMAEMA) or 25 °C (HEMA): [monomer]$_0$/[H-(MMA)$_2$-Cl]$_0$ = 100; [monomer]$_0$ = 500 mM (PEGMA) or 2000 mM (HEMA, DMAEMA); [Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.5 mM; [P(mTol)$_3$]$_0$ = 4.0 mM; [2-DMAE]$_0$ = 10 mM (PEGMA, DMAEMA) or 100 mM (HEMA). Monomer: PEGMA (●); HEMA (▲); DMAEMA (■). See Figure 1 for SEC curves for PEGMA.

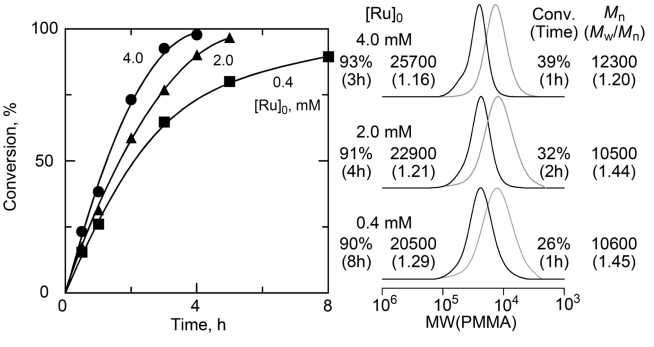


Figure 4. Reduction of catalyst dose in the polymerization of HEMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/4-DMAB in ethanol at 40 °C: [HEMA]$_0$ = 4.0 M; [H-(MMA)$_2$-Cl]$_0$ = 40 mM; [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 1.0, 0.5, or 0.1 mM; [P(mTol)$_3$]$_0$ = 8.0, 4.0, or 0.8 mM; [4-DMAB]$_0$ = 100 mM. Catalyst concentration: 4.0 mM (●); 2.0 mM (▲); 0.4 mM (■).

Reduction of Catalyst Dose. Such a high catalytic activity of the [Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE system for HEMA in ethanol further encouraged us to reduce the Ru complex concentration from 4.0 mM to as low as 0.10 mM (25 ppm relative to monomer): [HEMA]$_0$/[initiator]$_0$/[2-DMAE]$_0$ = 4000/40/100 mM; [Ru]$_0$ = 4.0, 2.0, 0.4, or 0.1 mM; initiator = H-(MMA)$_2$-Cl (Figure 4). Upon reducing the catalyst dose stepwise from 4.0 to 0.40 mM (100 ppm to monomer), the rate gradually decreased and MWD slightly broadened, but the polymerization was still fast enough to surpass 90% conversion in 8 h and retained reasonably narrow distributions (M_w/M_n = 1.29). Even at 0.10 mM ruthenium (25 ppm to monomer), conversion reached 93% in 12 h, though with a considerable broadening in MWD (M_w/M_n = 1.67). Thus, the catalytic system was active enough to lower the catalyst loading without serious loss of fine reaction control. Similar catalyst reductions were also possible for PEGMA and DMAEMA (see the Supporting Information).

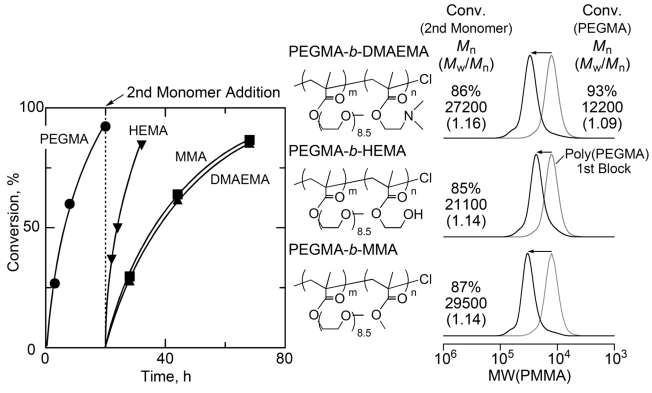


Figure 5. Block copolymerization of PEGMA with DMAEMA, HEMA, or MMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE in ethanol at 40 °C: [PEGMA]$_0$ = 0.5 M; [H-(MMA)$_2$-Cl]$_0$ = 20 mM; [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.5 mM; [P(mTol)$_3$]$_0$ = 4.0 mM; [2-DMAE]$_0$ = 10 mM; [DMAEMA]$_{add}$ = 4000 mM; [HEMA]$_{add}$/[2-DMAE]$_{add}$ = 1000/90 mM; [MMA]$_{add}$/[2-DMAE]$_{add}$ = 4000/90 mM. Monomer: PEGMA (●), DMAEMA (▲), HEMA (▼), MMA (■).

Block Copolymerization. With the common catalyst system for the three functional methacrylates, [Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE with H-(MMA)$_2$-Cl, a series of block copolymerizations were examined in ethanol at 40 °C (Figure 5). For example, PEGMA was first polymerized to 93% conversion, at which stage a second monomer (DMAEMA, HEMA, or MMA in bulk) was added to the as-polymerized reaction mixtures. Invariably the added monomers were almost quantitatively consumed. The initial poly(PEGMA) was of a narrow MWD (M_w/M_n = 1.09) that, during the second stage, cleanly shifted to higher molecular weight without a tailing and a serious broadening (M_w/M_n < 1.2). These results also demonstrate facile and undisturbed cross-propagation processes among the

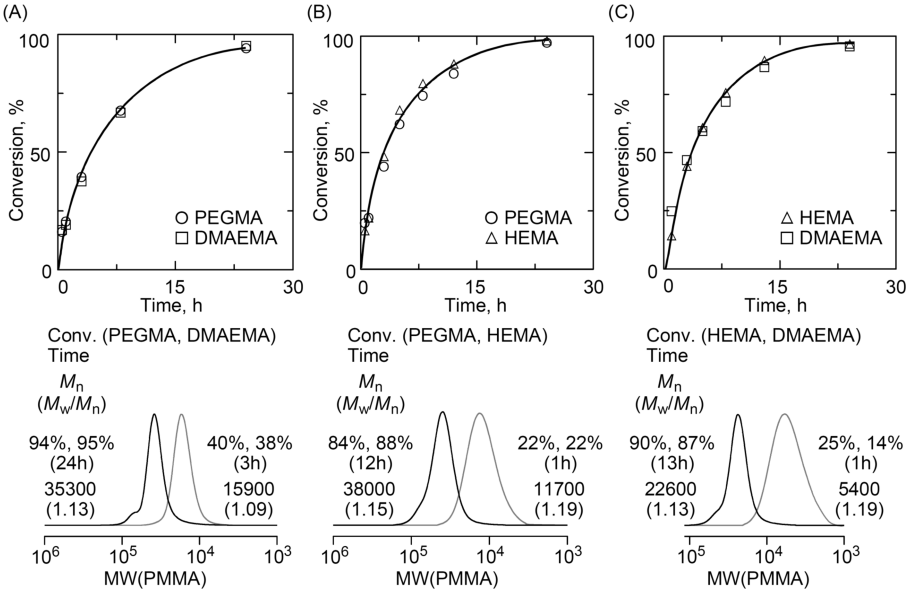


Figure 6. Random copolymerization of two monomers from PEGMA, DMAEMA, and HEMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE in ethanol at 40 °C: [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.5 mM; [P(mTol)$_3$]$_0$ = 4.0 mM. (A) [PEGMA]$_0$/[DMAEMA]$_0$/[H-(MMA)-Cl]$_0$/[2-DMAE]$_0$ = 500/500/10/10 mM; (B) [PEGMA]$_0$/[HEMA]$_0$/[H-(MMA)-Cl]$_0$/[2-DMAE]$_0$ = 500/500/10/100 mM; (C) [DMAEMA]$_0$ /[HEMA]$_0$/[H-(MMA)-Cl]$_0$/[2-DMAE]$_0$ = 1000/1000/20/100 mM. Monomer: PEGMA (○), DMAEMA (□), HEMA (△).

three methacrylates, despite their difference in pendent functionality and steric bulkiness.

Random Copolymerization. The undisturbed cross-propagation also led to living random copolymerizations of the three functional methacrylates in varying combinations, e.g., PEGMA/DMAEMA, PEGMA/HEMA, and HEMA/DMAEMA. Figure 6 shows the time−conversion and SEC profiles therein. Note that the total monomer concentrations were varied according to their combinations, so as to achieve the best catalytic performance. In every case, the two comonomers were consumed almost the same rates up to high conversion, indicating copolymers of statistical or random enchainments; namely, the apparent monomer reactivity ratios are close to unity and the differential as well as the integral copolymer compositions are 1:1. SEC analysis shows living copolymerization proceeding, as judged from continuing peak shifts in MWD and linear increase in M_n with conversion, as well as narrow MWDs ($M_w/M_n < 1.2$). Also important is that the internal compositional uniformity is high in these copolymers (i.e., "uniform" copolymers in which all copolymer chains within a single sample have nearly the same composition).

To demonstrate the versatility of the ethanol-mediated [Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE catalytic system, it was applied for a multiple random copolymerization of six methacrylates: PEGMA, HEMA, DMAEMA, MMA, dodecyl methacrylate (DMA), and benzyl methacrylate (BzMA) (Figure 7). All the monomers were smoothly consumed at similar rates, though a little different from one to another upon closer inspection of the time−conversion profiles, and finally they are quantitatively consumed in 30 h. The SEC-based apparent M_n (PMMA calibration) was in direct proportion to total monomer conversion, with narrow MWDs ($M_w/M_n < 1.2$).

These observations show, perhaps for the first time in metal-mediated living radical polymerization, a six-component living random copolymerization, despite the considerable difference in pendent architectures and polarity among the comonomers where hydrophobic (MMA, DMA, and BzMA) and hydrophilic (PEGMA, HEMA, and DMAEMA) are

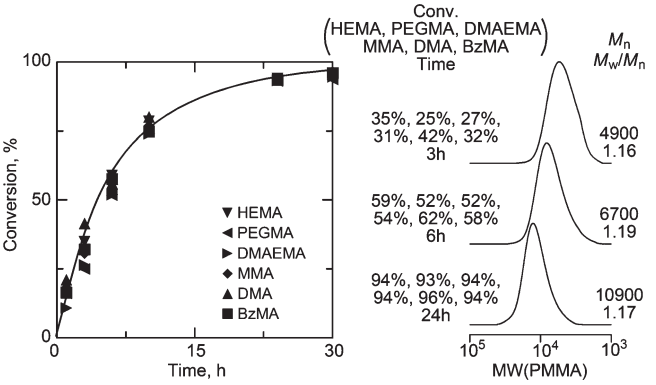


Figure 7. Hexa-random copolymerization of PEGMA, HEMA, DMAEMA, MMA, DMA, and BzMA with H-(MMA)$_2$-Cl/[Cp*Ru(μ_3-Cl)]$_4$/P(mTol)$_3$/2-DMAE in ethanol at 40 °C: [PEGMA]$_0$ = [HEMA]$_0$ = [DMAEMA]$_0$ = [MMA]$_0$ = [DMA]$_0$ = [BzMA]$_0$ = 200 mM; [H-(MMA)$_2$-Cl]$_0$ = 10 mM; [[Cp*Ru(μ_3-Cl)]$_4$]$_0$ = 0.5 mM; [P(mTol)$_3$]$_0$ = 4.0 mM; [2-DMAE]$_0$ = 100 mM. Monomer: PEGMA (left-pointing ▲), HEMA (▼), DMAEMA (right-pointing ▲), MMA (◆), MMA (▲), BzMA (■).

combined in feed. Thus, the ethanol-mediated Cp*Ru catalytic system was found to be highly active, functionality-tolerant, and versatile at least for methacrylates.

Conclusions

The [Cp*Ru(μ_3-Cl)]$_4$/P(m-Tol)$_3$/2-DMAE catalyst system in ethanol was found to be useful for living radical homo-, block, and random (co)polymerizations of a variety of alkyl and functionalized methacrylates. The catalytic activity was high enough to catalyze fast and controlled polymerizations regardless of the pendent functionality examined herein and also to reduce the ruthenium amount ([Ru]$_0$/[initiator]$_0$ ∼ 1/100; minimum 25 ppm to monomer) without a considerable loss of catalytic performance and reaction control, as attested by M_n proportional to conversion and narrow MWDs ($M_w/M_n < 1.2$). The wide range of available monomers is also suited for the controlled synthesis of "uniform" random copolymers, sometimes of as

many as six components with varying pendent polarity, hydrophilicity/hydrophobicity, and functionality.

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Supporting Information Available: We also examined a homopolymerization of PEGMA or DMAEMA with a reduced catalyst dose. This material is available free of charge via the Internet at http://pubs.acs.org.

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