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Phosphine–Ligand Decoration toward Active and Robust Iron Catalysts in LRP

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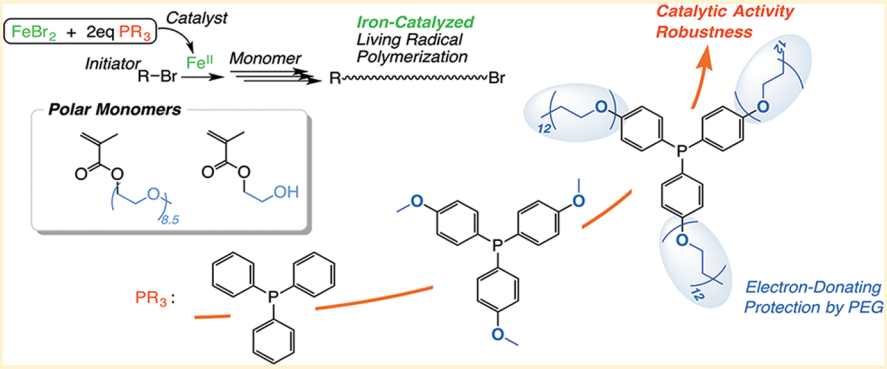
Supporting Information



ABSTRACT: Phosphine ligands were designed to enhance the catalytic activity of iron(II) complexes $[FeBr_2(PR_3)_2]$ for metal-catalyzed living radical polymerization (LRP), and special efforts were directed to the improvement in catalytic activity and robustness against functional monomers. Introduction of an electron donating group {methoxy $[P(MeOPh)_3]$ or *N,N′*-dimethylamino $[Ph_2P(Me_2NPh)]$} onto the *para* position of triphenyl phosphine (PPh_3) allowed active and robust Fe(II) complexes that catalyzed LRP of poly(ethylene glycol) methacrylate (PEGMA) smoothly proceeding to high conversion (~90%), to form polymers of controlled molecular weights and its distributions (M_w/M_n < 1.2). In contrast, such an enhancement was absent with the parent ligand PPh_3 and those with electron-withdrawing substituents. Furthermore, the replacement of the three methoxy groups in $P(MeOPh)_3$ with PEG chains led to a more robust catalyst, especially tolerant of the hydroxyl group in 2-hydroxyethyl methacrylate (HEMA). Accordingly, this catalyst enabled a four-component random living copolymerization of HEMA, PEGMA, and two alkyl methacrylates, where all the monomers randomly copolymerized into statistical copolymers of controlled molecular weights.

INTRODUCTION

Metal-catalyzed living radical polymerization (LRP),[1,2] or atom transfer radical polymerization,[3,4] has been developed to provide easy-to-use synthetic tools for well-defined polymers, block copolymers, and polymer conjugates, among others. Therein a metal complex (Mt^n) is in charge of the one-electron redox catalysis ($Mt^n \leftrightarrow XMt^{n+1}$) that reversibly activates the carbon–halogen (C–X) bond of an initiator (R–X) or the growing terminal ("dormant" species) into a carbon radical, along with the regeneration of the dormant end. The reversibility allows reduction of the instant concentration of "active" radical species and thus suppresses bimolecular termination and other unfavorable side-reactions inherent in the conventional free radical polymerization. In addition, the designability of initiating systems (initiators plus catalysts), coupled with their high initiation efficiency, has now positioned the metal-catalyzed LRP as a user-friendly, reproducible, and extensively applicable versatile synthetic strategy in various fields requiring well-defined polymeric architectures, often beyond polymer chemistry toward biochemistry, medicine, materials science, and other fields. However, the use of metal complex catalysts causes some disadvantages particularly in practical applications: metal contamination in products, expensiveness of metal, and low sustainability (rare and/or toxic metals).

Iron (Fe) belongs to the group 8 transition metal and mainly assumes the +2 and +3 oxidation states, thus qualified to the catalyst of the LRP requiring one-electron redox property. As an element, iron should be more attractive for LRP catalysts than often-used transition metals such as ruthenium (Ru)[5] and copper (Cu),[6] because "ferrum" is abundant on Earth, inexpensive, sustainable, and possibly safer. Indeed, industries are ardently requiring active and useful iron catalysts that may lead to practical application of LRP. Additionally, the important roles of iron-mediated redox systems ubiquitously found in biology and biological systems indicate the high biocompatibility and possible bioapplications of iron catalysts.

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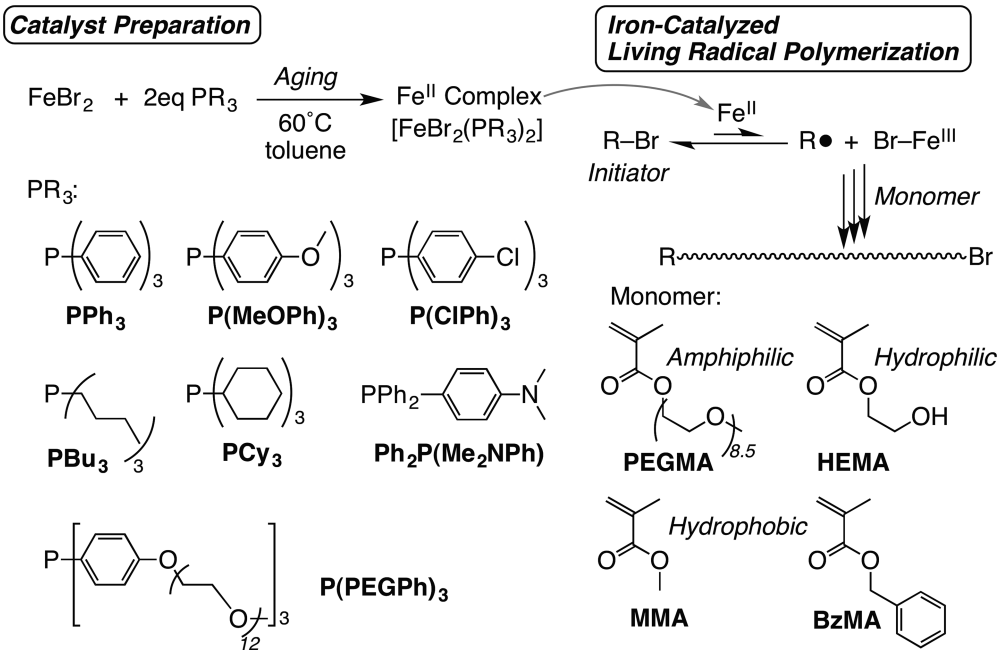
Scheme 1. Preparation of Iron Complexes with Various Phosphine Ligands and Iron-Catalyzed LRP



Some research groups, including ours,[7−17] have in fact already developed Fe catalysts for LRPs,[18−39] but they still seem inferior in activity and functionality-robustness to Ru- and Cu-based counterparts. A disadvantage on iron catalysts is a low tolerance to polar groups: For example, most of the hitherto developed iron LRP catalysts cannot survive in the presence of polar functionality in monomer or in solvent, often transformed into undesirable, much less active or inactive forms via ligand dissociation or ligand exchange. To our knowledge, the reported iron-catalyzed LRP systems, including those by us, have in fact been still poorly versatile in terms of applicable monomers and reaction conditions, often accessible to only "common" monomers such as alkyl (meth)acrylates and styrene derivatives without polar and functional pendent groups. Although some Fe-catalyzed LRPs have recently been reported for functional monomers, the controllability, i.e., livingness of growing end or efficiency in block copolymerization, is still unsatisfactory.[14,16,23,39] Given redox catalysis of some biological iron complexes in polar and aqueous environments, the previous efforts in ligand design have obviously been so insufficient that we could not educe the potential ability of iron catalysts for LRP of functional monomers yet.

These backgrounds have encouraged us to design new phosphine ligands for iron complexes toward really "applicable" iron catalysis of LRP for functional monomers and in polar or aqueous media. In this work, various phosphine ligands were designed and selected, and simple procedures were applied where they were mixed and aged with $FeBr_2$ in an organic solvent. The in situ formed phosphine-ligated Fe(II) complexes were directly employed as catalysts for LRP of functional monomers, such as HEMA and PEGMA [CH_2═$C(CH_3)$-$COO(CH_2CH_2O)_nCH_3$; n = 8.5 (number-average)], along with MMA and other nonpolar alkyl methacrylates (Scheme 1). Focus was directed to the electronic effects of the phosphine ligands on catalysis and to the steric effects that may protect the "central" iron from polar groups.

This paper is to report that the catalytic activity of iron complex can be enhanced by the introduction of electron donating and sometimes amphiphilic or hydrophilic groups onto triphenylphosphine and that the ligand decoration with polar and bulky PEG chain improves tolerance to highly polar groups, leading to controlled polymerization of functional monomers.

EXPERIMENTAL SECTION

Materials. MMA (Tokyo Kasei; > 99%) was dried overnight over calcium chloride, and distilled from calcium hydride under reduced pressure before use. HEMA (Aldrich; > 99%) was distilled under reduced pressure before use. BzMA (TCI; > 98%) and PEGMA [CH_2═$C(CH_3)COO(CH_2CH_2O)_nCH_3$; n = 8.5 (number-average)] (Aldrich) were purified by passing through an inhibitor-removal column (Aldrich) and were subsequently degassed by three-time vacuum-argon bubbling cycles before use. The $H(MMA)_2Br$ initiator [$H(CH_2CMeCO_2Me)_2Br$; an MMA dimer bromide] was prepared according to the literature.[40] $FeBr_2$ (Aldrich; 98%) and ligands [PPh_3 (Aldrich; 99%), $P(MeOPh)_3$ (Wako; > 98%), $P(ClPh)_3$ (Aldrich; 95%), PBu_3 (Strem; 99%), PCy_3 (Aldrich), and $Ph_2P(Me_2NPh)$ (Aldrich; 95%)] were used as received and handled in a groove box under a moisture- and oxygen-free argon atmosphere (H_2O < 1 ppm, O_2 < 1 ppm). Toluene (Kishida Kagaku; purity 99.5%) was dried and purified by passing through purification columns (Solvent Dispensing System, SG Water USA, Nashua, NH; Glass Contour) and bubbled with dry nitrogen for more than 15 min immediately before use. *n*-Octane (internal standard for gas chromatography) and 1,2,3,4-tetrahydrousnaphthalene (tetralin; internal standard for ^1H NMR) were dried over calcium chloride and distilled twice from calcium hydride. Poly(ethylene glycol) monomethyl ether [$HO(CH_2CH_2O)_nMe$; n = 12 on average] (Aldrich), *p*-toluenesulfonyl chloride (Aldrich; > 99%), pyridine (Wako; dehydrated), H_2O_2 (TCI; 35% in water), BBr_3 (TCI; ca. 1 M in CH_2Cl_2), phenylsilane (TCI; > 97%), NaOH (Wako; > 97%), HCl (Wako; 35−37% in water), Na_2SO_4 (Wako; > 99%), K_2CO_3 (Wako; > 99.5%), NaCl (Wako; > 99.5%), distilled water (Wako), CH_2Cl_2 (Wako; super dehydrated), DMF (Wako; super dehydrated), acetone (Wako; super dehydrated), and ethyl acetate (Wako; > 99.5%) were used as received.

Synthesis of $P(PEGPh)_3$.[41] *Synthesis of Tris(4-hydroxyphenyl)-phosphine Oxide [O═P(MeOPh)$_3$].* To a solution of $P(MeOPh)_3$

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(5.00 g, 14.2 mmol) in acetone (50 mL), water (3.33 mL) and H_2O_2 (35-% solution, 1.67 mL; 15 mmol) were slowly added. After stirring at room temperature for 1 h, the acetone was evaporated and CH_2Cl_2 (80 mL) was added. The organic layer was washed with brine (3 × 35 mL), the aqueous solution was extracted with CH_2Cl_2 (2 × 25 mL), and the combined organic solutions were dried over anhydrous Na_2SO_4. After filtration, the filtrate was evaporated under vacuum to give white solid (86% yield).

Synthesis of Tris(4-hydroxyphenyl)phosphine Oxide [O═P-(HOPh)$_3$]. A solution of BBr_3 (1 M in CH_2Cl_2; 50 mL, 50 mmol) was slowly added at −78 °C to a solution of O═P(MeOPh)$_3$ (3.68 g, 10 mmol) in CH_2Cl_2 (35 mL) under argon. After being stirred at room temperature for 24 h, the solution was slowly poured into cold water (130 mL). After evaporation of CH_2Cl_2, the aqueous phase was filtered and extracted with ethyl acetate (3 × 100 mL). The combined organic phases were washed with brine (2 × 10 mL). After evaporation of the solvent, recrystallization from ethyl acetate gave white solid (81% yield).

Synthesis of Poly(ethylene glycol) Methyl Ether Tosylate [TsO-PEG]. To a solution of poly(ethylene glycol) monomethyl ether (HO-PEG) (12.5 g, 22.7 mmol) and *p*-toluenesulfonyl chloride (8.66 g, 45.4 mmol) in CH_2Cl_2 (40 mL) was slowly added pyridine (3.66 mL, 45.4 mmol). The resulting solution was stirred at room temperature for 15 h. After water (10 mL) was added, NaOH was carefully added until the aqueous layer became neutral. The organic layer was washed with 1 N HCl (aq) and brine, successively. The organic layer was dried over anhydrous Na_2SO_4. After filtration, the filtrate was evaporated under vacuum to give pale yellow oil (77% yield).

Synthesis of O═P(PEGPh)$_3$. A suspension of TsO-PEG (2.13 g, 3.05 mmol), O═P(HOPh)$_3$ (1.00 g, 3.05 mmol) and K_2CO_3 (4.21 g, 30.5 mmol) in DMF (70 mL) was stirred at 70 °C for 24 h under Ar. After removal of volatiles under vacuum, the residue was dissolved in CH_2Cl_2. The organic layer was washed with 1 N HCl (aq) and brine, successively. The organic layer was dried over anhydrous Na_2SO_4. After filtration, the filtrate was evaporated under vacuum (77% yield). ^{31}P NMR (202 MHz, $CDCl_3$): δ 33.9.

Synthesis of P(PEGPh)$_3$. A solution of O═P(PEGPh)$_3$ (2.88 g, 1.50 mmol) and phenylsilane (3.41 mL, 30.0 mmol) in toluene (10 mL) was refluxed under argon for 24 h. After the reaction mixture was evaporated under vacuum, the residue was extracted with CH_2Cl_2 and washed with hexane. The removal of all the volatiles gave P(PEGPh)$_3$ (64% yield). Finally, the structure was characterized ^{1}H NMR (500 MHz, $CDCl_3$: Supporting Information) and ^{31} P NMR (202 Hz, $CDCl_3$: δ −4.50).

Polymerization Procedures. 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. A typical example for PEGMA polymerization with the H(MMA)$_2$Br/FeBr$_2$/P(MeOPh)$_3$ is given below. In a round-bottom flask (50 mL) was placed $FeBr_2$ (4.3 mg, 0.020 mmol), P(MeOPh)$_3$ (14.1 mg, 0.040 mmol), and toluene (2.91 mL) under argon gas. The solution was heated to 60 °C for 12 h to prepare bisphosphine iron complexes.[42] After cooling the mixture to room temperature, tetralin (0.06 mL), PEGMA (0.88 mL, 2.0 mmol), and a solution of H(MMA)$_2$Br (0.15 mL, 133.7 mM in toluene) were added; the total volume was 4.00 mL. Immediately after mixing, aliquots (0.50−1.0 mL each) of the solution were injected into baked glass tubes, which were then sealed (except when a stopcock was used) and placed in an oil bath kept at 60 °C. In predetermined intervals, the polymerization was terminated by cooling the reaction mixture to −78 °C in dry ice−methanol. Monomer conversion was determined by ^{1}H NMR from the integrated peak area of the olefinic protons of the monomer with tetralin as an internal standard. For MMA, the same procedures as described above were applied, except that monomer conversion was determined from residual monomer concentration measured by gas chromatography with *n*-octane as an internal standard.

Measurements. For polar (co)polymers of PEGMA or HEMA, M_n and M_w/M_n were measured by size exclusion chromatography at 40 °C in DMF containing 10 mM LiBr as an eluent on three polystyrene-gel columns (Shodex KF-805 L; exclusion limit =4 × 10^6; particle size =10 μm; pore size =5000 A; 0.8 cm i.d. × 30 cm; flow rate, 1.0 mL min^{-1}) connected to a PU-2080 pump and a RI-1530 refractive-index detector, and a UV-1570 ultraviolet detector (all from Jasco). The columns were calibrated against 13 standard poly(MMA) samples (Polymer Laboratories; M_n = 630−1 200 000; M_w/M_n = 1.02−1.30) as well as the monomer. For poly(MMA), M_n and M_w/M_n were measured by size exclusion chromatography at 40 °C in THF as an eluent on three polystyrene-gel columns (Shodex LF-404; exclusion limit = 2 × 10^6; particle size = 6 μm; pore size = 3000 Å; 0.46 cm i.d. × 25 cm; flow rate, 0.3 mL min^{-1}) connected to a DU-H2000 pump, a RI-74 refractive-index detector, and a UV-41 ultraviolet detector (all from Shodex), similarly calibrated against standard poly(MMA) samples. ^{1}H NMR and ^{31}P NMR spectra were measured at room temperature on a JEOL JNM-ECA500 spectrometer operating at 500.16 and 202.47 MHz, respectively. For the ^{31}P NMR analyses, a capillary of $(C_2H_5O)_2POH$ solution (50 mM in toluene-d_8) was used as an internal chemical shift standard (12 ppm for the phosphite).

RESULTS AND DISCUSION

Effects of the Electronic Properties with *Para*-Substituted Triphenyl Phosphines in PEGMA Polymerization. As shown in Scheme 1, 2 equiv of various phosphines (PR_3) were mixed with anhydrous iron dibromide ($FeBr_2$) in toluene, and the solutions were kept (aged) at 60 °C for 12 h hours, to in situ generate the corresponding bisphosphine iron complexes [$FeBr_2(PR_3)_2$]. The resultant iron complexes were directly employed as a catalyst for polymerization of PEGMA with a bromine initiator [H(MMA)$_2$Br] in toluene.

$FeBr_2(PPh_3)_2$, an iron catalyst with the most standard phosphine ligand, triphenyl phosphine (PPh_3), induced a slow polymerization, and monomer conversion was limited to below 30% (Figure 1). A ligand carrying an electron withdrawing

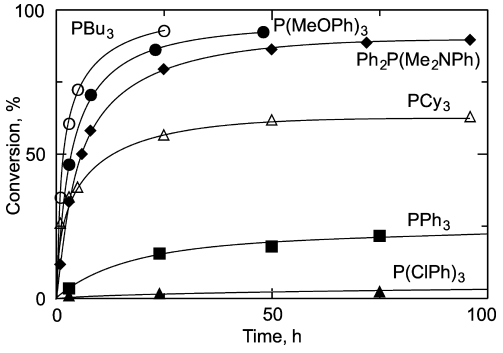

Figure 1. Effects of phosphine ligand on polymerization rate of iron-catalyzed polymerizations of PEGMA in toluene at 60 °C: [PEGMA]$_0$/[H(MMA)$_2$Br]$_0$/[Fe-complex]$_0$ = 500/5/5 mM. The Fe complex was prepared in prior to polymerization via aging process of $FeBr_2$ and 2 equiv of phosphine ligand in toluene at 60 °C in 12 h and directly employed without purification.

substituent [P(ClPh)$_3$] was further less effective, virtually without monomer consumption. In contrast, when phosphines with electron donating substituents [PBu_3, PCy_3, P(MeOPh)$_3$, and $Ph_2P(Me_2NPh)$] were employed, the polymerizations smoothly proceeded to give higher conversions.

Molecular weight and molecular weight distribution (MWD) of the poly(PEGMA) obtained with these phosphine-ligated catalysts were characterized by SEC (Figure 2). For electron-donating alkyl phosphines (PBu_3 and PCy_3), the SEC curves were broad and sometimes bimodal ($M_w/M_n \sim 2$), indicating uncontrolled polymerizations. However, with triphenyl phosphines carrying strongly electron-donating groups, such as

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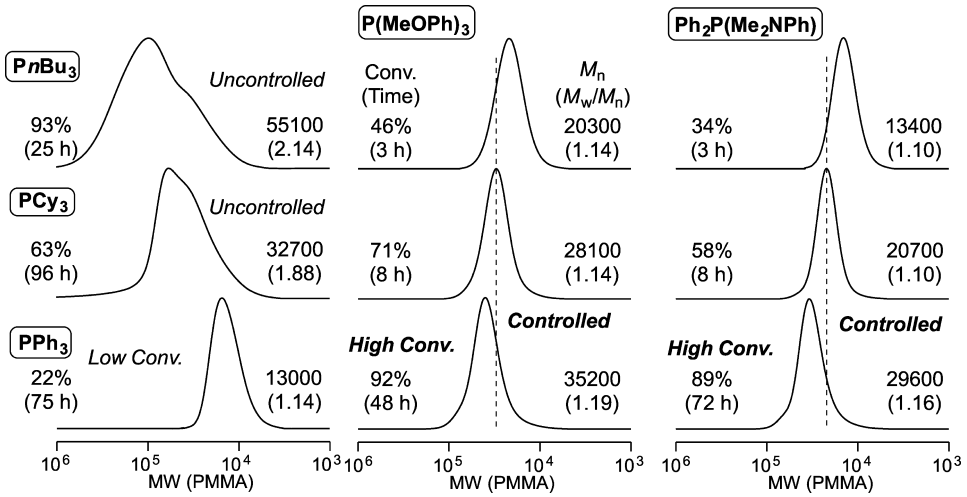

Figure 2. SEC curves of obtained polyPEGMAs to see effects of ligand on molecular weight control in iron-catalyzed radical polymerization of PEGMA. Polymerization conditions: see caption of Figure 1.

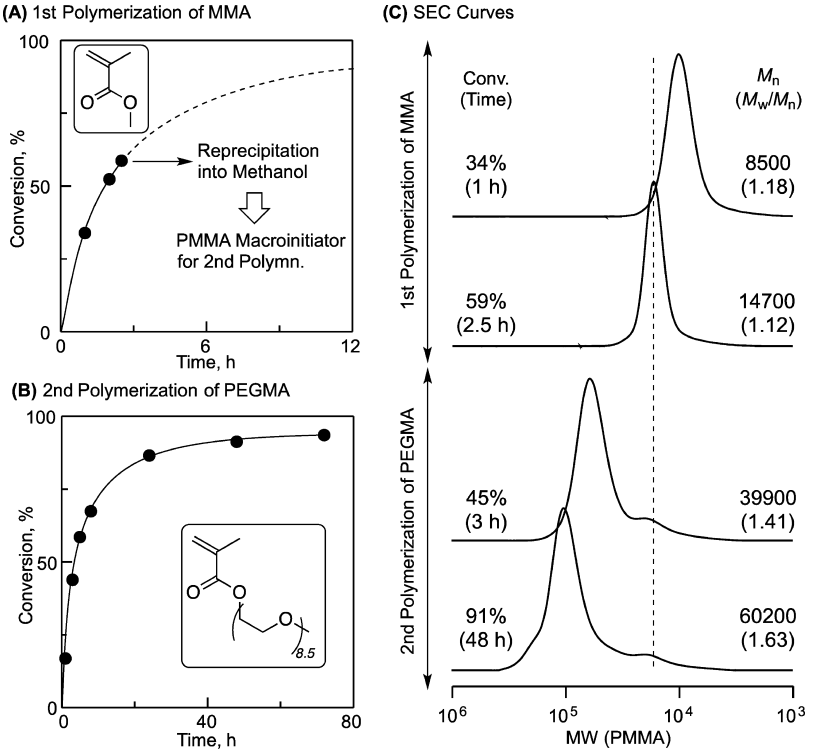

Figure 3. Iron-catalyzed block copolymerization of MMA and PEGMA with $FeBr_2$/$P(MeOPh)_3$ complex. (A) Polymerization for synthesis of PMMA-macroinitiator: $[MMA]_0/[H(MMA)_2Br]_0/[Fe\text{-}complex]_0$ = 4000/20/10 mM in toluene at 60 °C. (B) Polymerization for PMMA-*block*-PPEGMA: $[PEGMA]_0/[PMMA\text{-}macroinitiator]_0/[Fe\ complex]_0$ = 500/5/5 mM in toluene at 60 °C. The Fe complex was prepared in prior to polymerization via aging process of $FeBr_2$ and 2 equiv of $P(MeOPh)_3$ in toluene at 60 °C for 12 h and directly employed without purification for both polymerizations.

$P(MeOPh)_3$ and $Ph_2P(Me_2NPh)$, the polymerizations were fairly controlled: SEC curves shifted to higher molecular weight as conversion increased, while keeping narrow molecular weight distributions (M_w/M_n < 1.2). Thus, enhancement of the electron density on the iron center through triphenylphosphine ligands was important in the iron-catalyzed LRP of PEGMA. Please note that there are little examples of such active catalysts to achieve higher conversions (conv. ~90%) and narrow molecular weight distributions (M_w/M_n < 1.20).

Iron-Catalyzed Block Copolymerization of MMA with PEGMA with $P(MeOPh)_3$. Ligation of $P(MeOPh)_3$ on $FeBr_2$ was also effective for the LRP of alkyl methacrylates (MMA etc.) to give controlled polymers (Supporting Information). This result encouraged us to apply the methoxyphenyl complex for block copolymerization of MMA with PEGMA (Figure 3). To synthesize AB-type block copolymers, MMA was first polymerized. The resulting PMMA (with a halogen-capped dormant terminal) was separated and employed as a macroinitiator for the second-stage polymerization of PEGMA.

Thus, we first carried out MMA polymerization with $FeBr_2$/$P(MeOPh)_3$ and the bromide initiator in toluene at 60 °C: $[MMA]_0$ = 4.0 M; $[H(MMA)_2Br]_0$ = 20 mM; $[FeBr_2]_0$ = 10

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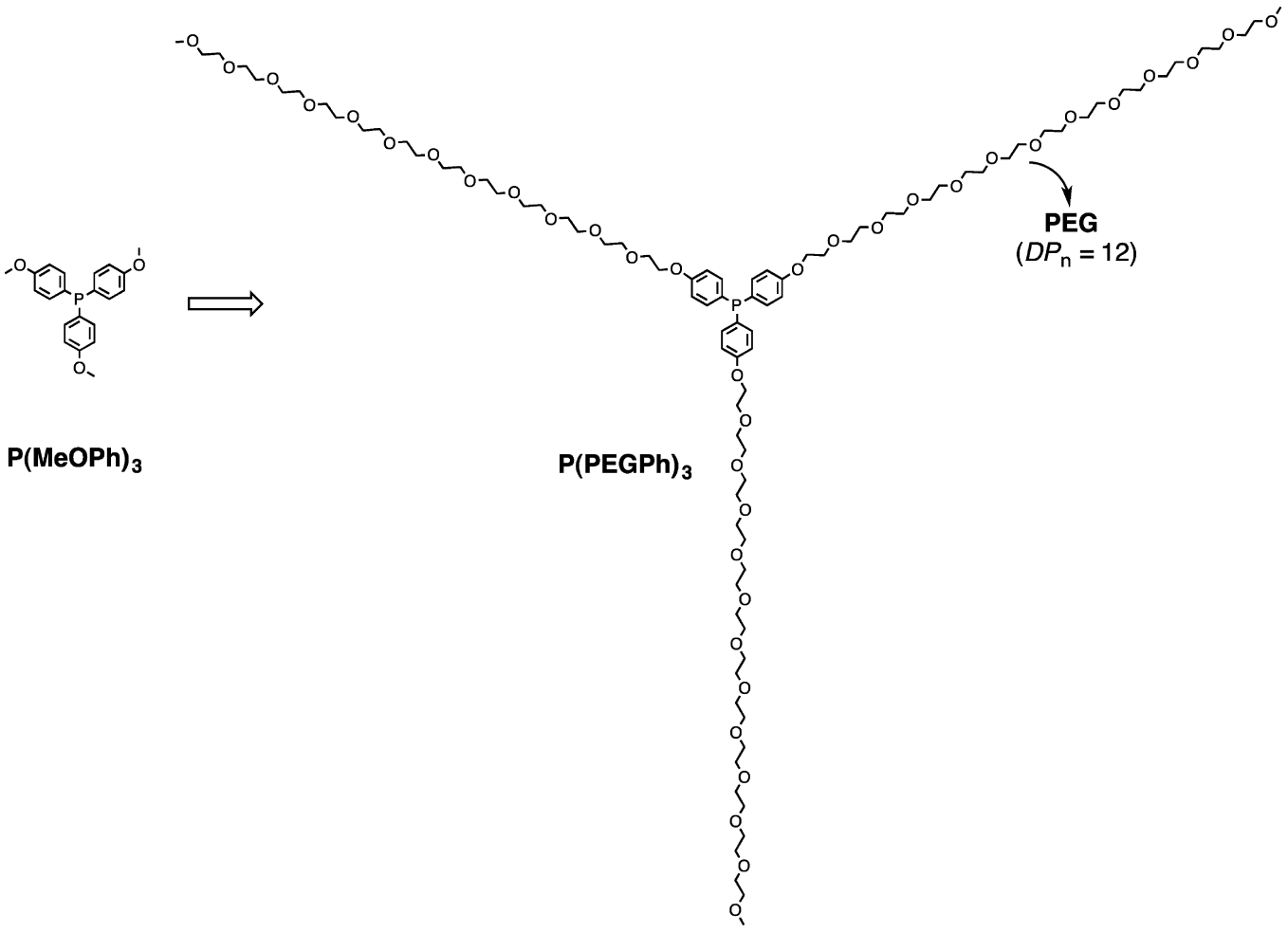

Figure 4. Decoration of *para*-substitution of triphenylphosphine with PEG chain.

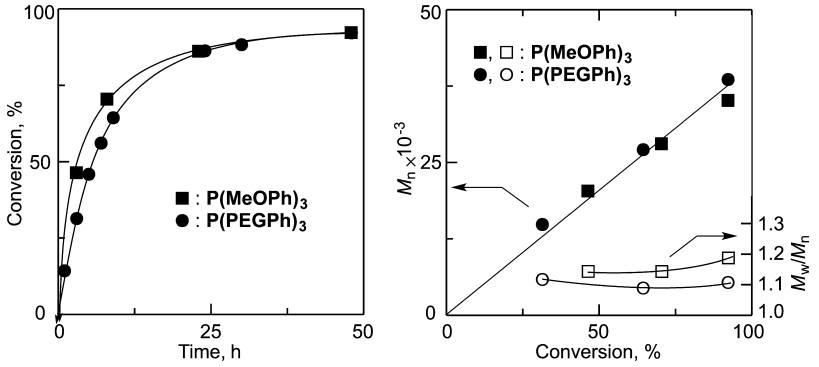

Figure 5. Conversion vs M_n and M_w/M_n plots for iron-catalyzed LRPs of PEGMA with $P(PEGPh)_3$ or $P(MeOPh)_3$ as a ligand in toluene at 60 °C: $[PEGMA]_0/[H(MMA)_2Br]_0/[Fe\text{-complex}]_0$ = 500/5/5 mM. Fe-complex was prepared in prior to polymerization via aging process of $FeBr_2$ and 2 equiv of phosphine ligand in toluene at 60 °C in 12 h and directly employed without purification.

mM; $[P(MeOPh)_3]_0$ = 20 mM. When conversion reached about 60% in 2.5 h, the polymerization was quenched, and reprecipitation into methanol gave a colorless sample of PMMABr (M_n = 14700; M_w/M_n = 1.12; terminal Br functionality >90% by ^1H NMR) (Figure 3A). The Br-capped polymer was employed to initiate PEGMA polymerization with a freshly aged catalyst [$FeBr_2$ and 2eq $P(MeOPh)_3$].

PEGMA conversion smoothly reached 91% in 48 h, as with the corresponding homopolymerization with $H(MMA)_2Br$. Thus, the catalytic activity was well retained in the two-stage consecutive block copolymerization. In the SEC curves of the final products, a very small peak was detected, indicative of some "dead" PMMA from the first-stage polymerization, but the main peak clearly shifted to higher molecular weight keeping narrow MWD.

Decoration with Polar Electron-Donating Substituents toward Robust Iron Catalyst. As shown above, the introduction of electron-donating phosphines was effective to enhance the catalytic activity of iron catalysts. However, these systems were confined to the use in toluene and related

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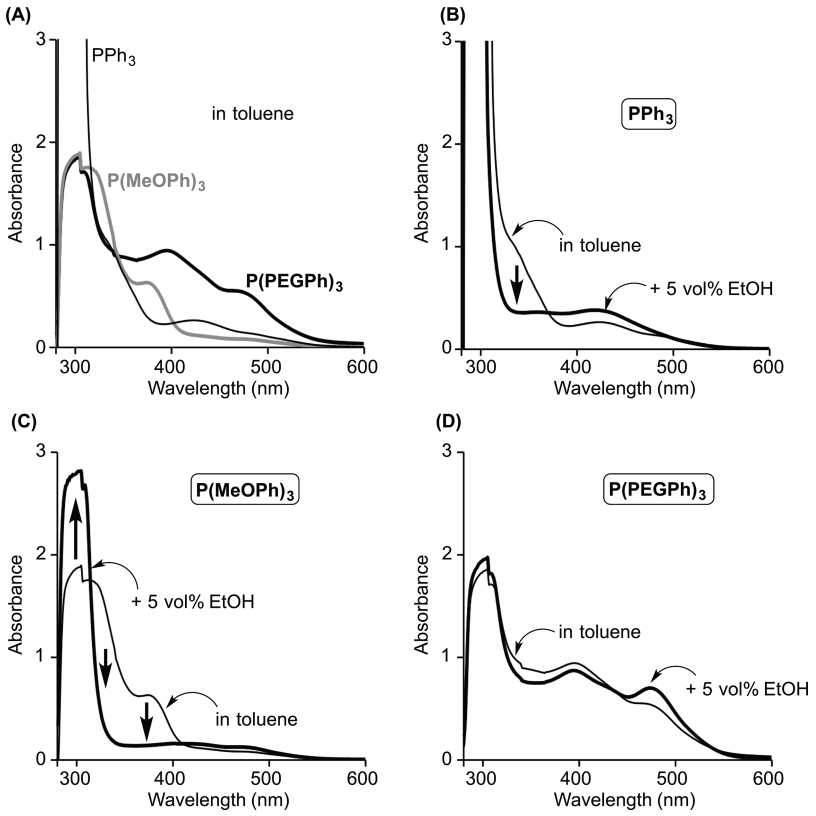

Figure 6. UV−vis spectra (280−600 nm) of $FeBr_2$ complexes with PPh_3, $P(MeOPh)_3$, and $P(PEGPh)_3$ in toluene or 5 vol % ethanol-contained toluene at room temperature: (A) comparison among the three complexes in toluene; (B−D) effects of ethanol addition on complexation [(B) PPh_3, (C) $P(MeOPh)_3$, (D) $P(PEGPh)_3$]. The Fe complex was prepared via aging process of $FeBr_2$ and 2 equiv of phosphine ligand in toluene at 60 °C in 12 h ($[FeBr_2]_0$ = 5.0 mM, $[ligand]_0$ = 10.0 mM). The aged solutions were diluted with toluene to make 1.0 mM concentration, followed by filtration for the measurement.

nonpolar media and seem not robust enough against polar groups such as hydroxyl. For example, a polymerization solution of PEGMA with $FeBr_2/P(MeOPh)_3$ immediately faded from original yellow into colorless upon addition of a few drops of methanol, suggesting dissociation of the ligands to form an unidentified phosphine-free iron complex or compound.

We thus embarked on an additional design of ligand to more effectively "protect" the iron center from potentially poisonous polar groups. Our focus was then directed to the replacement of the three methoxy groups ($-OCH_3$) in $P(MeOPh)_3$ with poly(ethylene glycol) chains [PEG: $-O(CH_2CH_2O)_{12}CH_3$] into a tris(PEG-lated phenyl)phosphine $P(PEGPh)_3$ (Figure 4). This decoration was based on the following aspects: (i) despite its polar and polyether character, PEG would not be so poisonous to iron complexes, as suggested by the successful PEGMA polymerization discussed above; (ii) the bulkiness and higher polarity of PEG would contribute to the protection of the central iron from polar groups, sterically, electronically, or both.

Catalytic Activity of Iron Complex with $P(PEGPh)_3$ on PEGMA Polymerization. To examine the catalytic activity of the $FeBr_2/P(PEGPh)_3$ system, we first performed PEGMA polymerization in toluene at 60 °C, under the same conditions as with $P(MeOPh)_3$. The aging with $FeBr_2$ gave a yellow homogeneous solution similar to that with the methoxy derivative, indicating a similar diphosphine ligation. The polymerization (Figure 5) was also comparable in terms of reaction rate (catalytic activity) as well as molecular weight and MWD control: M_n was linearly increased with conversion, and M_w/M_n was kept below 1.12. Namely, the three PEG chains on the *para* positions effectively enhance catalytic activity by electron-donation and perhaps protect the iron center, without entailing adverse effects.

Tolerance to Hydroxyl Group of Iron Catalysts: UV−vis Analysis. When a small portion of ethanol was added to a toluene solution of the $P(PEGPh)_3$−iron complex, the yellow color remained unchanged, in contrast to the fast discoloration of the $P(MeOPh)_3$ system (see above). The apparent robustness of the $P(PEGPh)_3$-complex was further evaluated by UV−vis spectroscopy.

Figure 6 shows UV−vis spectra (280−600 nm) of $FeBr_2$ complexes with three phosphine ligands [PPh_3, $P(MeOPh)_3$, and $P(PEGPh)_3$], either in the presence and the absence of ethanol. All the complexes were prepared by mixing and aging $FeBr_2$ and 2 equiv of each phosphine in toluene at 60 °C for 12 h, and the solutions, all yellow independent of the ligands, were subject to spectroscopic analysis without further purification and treatment. The spectra generally consisted two characteristic peaks, one at 320−400 nm most likely from charge-transfer or d−d transition and the other at ∼300 nm, indicative of a free phosphine (or ligand dissociation).

In the alcohol-free solutions (Figure 6A), the free ligand signal was very strong and off-scale with $FeBr_2(PPh_3)_2$, showing dominant ligand dissociation even in the nonpolar medium and thus the lower stability of the catalyst, as already pointed in the literature. On the other hand, free phosphine was much less detectable with $P(MeOPh)_3$ or $P(PEGPh)_3$, and the coordina-

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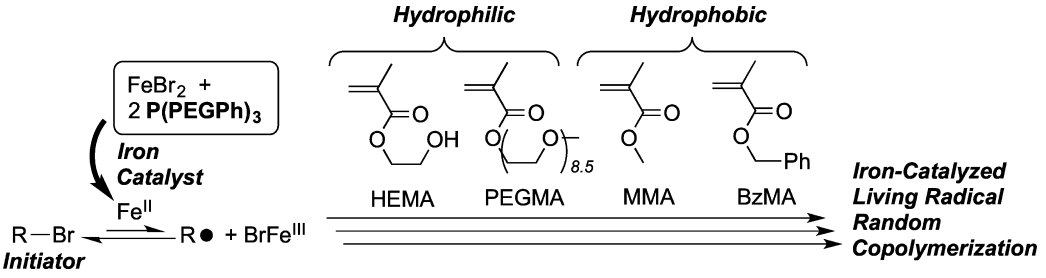
Scheme 2. Iron-Catalyzed Living Radical Random Copolymerization of HEMA, PEGMA, MMA, and BzMA with $FeBr_2$–$P(PEGPh)_3$ Complex



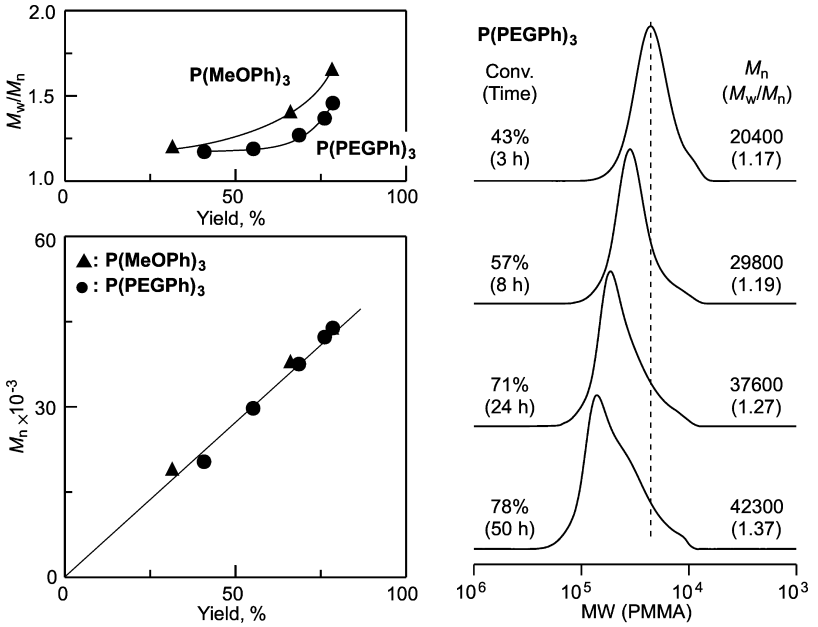


Figure 7. Iron-catalyzed living radical random copolymerization of HEMA, PEGMA, MMA and BzMA with $FeBr_2$–$P(PEGPh)_3$ complex in toluene at 60 °C: $[HEMA]_0/[PEGMA]_0/[MMA]_0/[BzMA]_0/[H(MMA)_2Br]_0/[Fe\ complex]_0$ = 250/250/250/250/5/5 mM. The Fe complex was prepared in prior to polymerization via aging process of $FeBr_2$ and 2 equiv of $P(PEGPh)_3$ in toluene at 60 °C in 12 h and directly employed without purification.

tion of these *para*-substituted electron-donating ligands was relatively tight and effectively enriches electron density of the iron center.

Upon addition of ethanol (5 vol %), the yellow solutions with PPh_3 and $P(MeOPh)_3$ immediately faded into colorless, while the free ligand signal enhanced and the red-shifted transition signals weakened [Figure 6 (B) and (C)]. All these indicate facile decomposition, or lesser stability, of the two complexes. Rather antithetically, the $P(PEGPh)_3$-complex is apparently much more resistant to alcohol; the solution remained yellow and the whole spectrum was hardly changed (Figure 6D), unless the added ethanol was in excess over 5 vol %. These analyses supported that PEG-lated phosphine-iron complex is relatively robust and tolerant of alcohol or hydroxyl group.

Random Copolymerization of PEGMA with HEMA. The above results with UV–vis analyses encouraged us to employ $FeBr_2/P(PEGPh)_3$ for polymerizations of functional polar monomers and specifically for quaternary random copolymerization of methacrylates [HEMA, PEGMA, MMA, and benzyl methacrylate (BzMA): Scheme 2]. Control of such a multicomponent random copolymerization of functionalized monomers is important for industrial applications, particularly with an iron catalyst.

The four monomers were smoothly consumed at similar rates, although HEMA conversion was a little higher (Supporting Information), and conversion reached over 70% in 24 h for each component [87% (HEMA); 65% (PEGMA); 64% (MMA); 67% (BzMA)]. As shown in Figure 7, M_ns of obtained copolymers were linearly increased with copolymer yield (calculated from conversion). At the initial stages, narrow MWDs were observed (M_w/M_n < 1.20), but the SEC curves broadened as the polymerization proceeded, and minor peaks of apparently dead polymers chains were detected. However, the M_w/M_n values were lower than with $P(MeOPh)_3$, likely due to higher tolerance to the hydroxyl group.

■ CONCLUSION

In this paper, we have approached robust iron-catalyzed LRPs via modification of phosphine ligand. An introduction of electron donating (i.e., methoxy- or dimethylamino) of the bis(phosphine)iron complex $[FeBr_2(PR_3)_2]$ dramatically increased polymerization rate up to higher conversion for PEGMA; nevertheless, the polymerization was well controlled to give narrow molecular weight distributions (M_w/M_n < 1.2).

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The high catalytic activity allowed iron-catalyzed block copolymerization of MMA with PEGMA. In addition, polar macromolecular (i.e., PEG) substituents on ligand were particularly effective for an enhancement of catalytic activity of polymerization of HEMA as well as PEGMA due to protection effect of iron center from polar groups. However, it was still difficult to control polymerizations of more polar monomers, such as dimethylaminoethyl methacrylate, methacrylic acid, even with the iron catalyst of the PEG-decollated ligand. Thus, our next efforts would be directed to other iron precursors instead of $FeBr_2$ to be combined with the related designer phosphine ligands toward more robust and applicable iron catalysts.

■ ASSOCIATED CONTENT

Supporting Information

^1H NMR spectra for synthesis of $P(PEGPh)_3$, iron-catalyzed living radical polymerization of MMA with $FeBr_2$−$P(MeOPh)_3$ complex, and time vs conversion plots for iron-catalyzed living radical random copolymerization of HEMA, PEGMA, MMA, and BzMA. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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