Metallopolymers in Minutes *via* Organocatalysis at Room Temperature

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Metallopolymers in Minutes *via* Organocatalysis at Room Temperature

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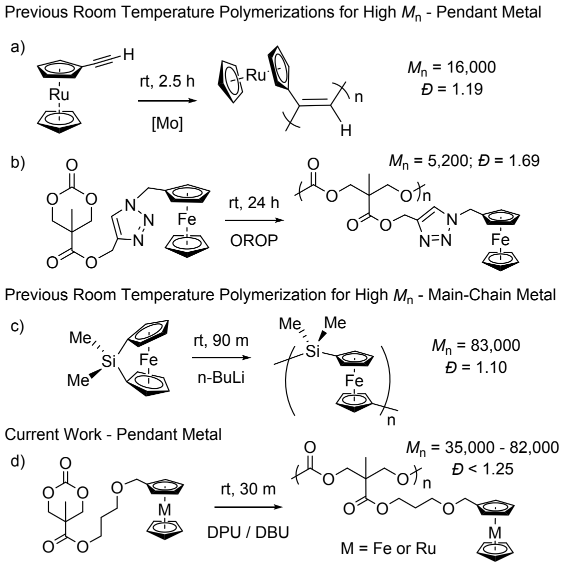
ABSTRACT

The organocatalytic ring-opening polymerization (OROP) of cyclic carbonate monomers derivatized with metallocenes is described for the rapid synthesis of high M_n metallopolymers where the metal is pendant to the polymer backbone. This work bridges the fields of organocatalysis and metallopolymers and establishes a new paradigm that metallic monomers can be compatible with OROP.

TEXT OF COMMUNICATION

Advances in metallopolymer synthesis have led to new applications in many fields including biomedicine, catalysis, stimuli-responsive and sensing materials, optics, electrolytes, energy storage, drug delivery, and magnetic materials.[1–7] Two common locations for the metal in metallopolymer architectures are in the polymer main-chain, or as a pendant group tethered to the polymer backbone.[8] The best main-chain metallopolymer synthetic strategies arguably continue to be the ring-opening polymerization (ROP) of strained metallocenophanes, as developed by Manners, because of their good speed and control.[9–12] Syntheses of diverse metallopolymers with pendant metal groups tethered to the polymer backbone have been accomplished by many strategies, including polymerization of vinyl, acrylate, or epoxy monomers bound to metal complexes,[13–21] ring-opening metathesis polymerization (ROMP) of norbornyl-substituted metal complexes,[22,23] and post-polymerization metalation of polymers with metal binding sites.[14,24] Despite these successes, metallopolymer synthesis remains notoriously difficult, and new synthetic strategies are needed that are fast, controlled, and compatible with existing monomer classes. In this communication, organocatalytic ring-opening polymerization (OROP) is presented as a rapid strategy for the room-temperature synthesis of high molecular weight metallopolymers and block copolymers where the metal groups are pendant to the polymer backbone.

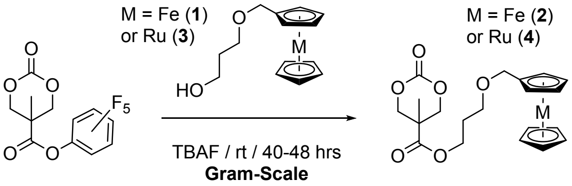
Examples of metallopolymer synthesis with pendant metal complexes at room temperature are scarce in the literature, and relevant homopolymers are summarized here. Schrock-based molybdenum metathesis catalysts can be used to rapidly polymerize ethynylferrocene and ethynylruthenocene monomers or a norbornene monomer with a pendant ferrocene in reaction times ranging from 15 minutes to 2.5 hours (Scheme 1a), but the size of the polymers are often limited by their solubilities and have low molecular weights (M_n's = 5,090 – 16,400).[22,25] The OROP of cyclic carbonate monomers and lactone monomers tethered to ferrocene with a triazole linker has been attempted by others (Scheme 1b), but reaction times were long (12-24 hours) and only low molecular weight polycarbonates (M_n = 4,000 – 5,200) were isolated (the lactone monomers did not react).[26] Attempting to synthesize metallopolymers at room temperature using reversible addition-fragmentation chain-transfer (RAFT) or dehydrocoupling polymerizations, when the optimized conditions called for heating, resulted in long reaction times and low conversions.[27,28] By way of comparison, main-chain metallopolymers have had much greater success in room temperature polymerizations, as evidenced by the anionic ring-opening polymerization of silicon-bridged [1]ferrocenophanes initiated by *n*-butyllithium (Scheme 1c, 90 min, M_n = 83,000).[10] Herein, we describe a rapid (30 min), room-temperature OROP system that provides access to high molecular weight metallopolymers containing pendant metal groups (Scheme 1d, M_n = 35,000 – 82,000). This system surpasses the molecular weight previously attainable for room temperature polymerization of monomers with pendant metal groups, and rivals the best main-chain metallopolymerization systems.



Scheme 1. Representative examples of known metallopolymer syntheses at room temperature. (a) Metathesis polymerization of a polyene with pendant metallocenes. (b) OROP of cyclic carbonates with pendant metallocenes tethered by a triazole linker. (c) Anionic ring-opening

polymerization of a metallocenophane to make a main-chain metallopolymer. (d) Current work – OROP of cyclic carbonates with pendant metallocenes attached by a 1,3-propanediol linker.

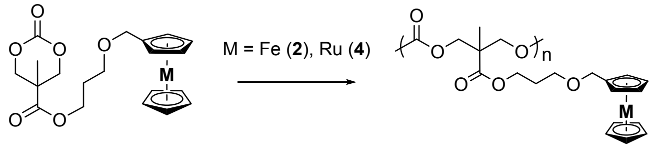
For our investigation, we targeted metal-containing cyclic carbonate monomers **2** and **4** as shown in Scheme 2. While the only previous report of OROP with metallic monomers yielded low molecular weight polymers, those monomers utilized a triazole linker.[26] Since polymerizations of strictly organic monomers bearing triazole functional groups have also been reported to give low molecular weights (M_n = 2,300 and 5,600),[29] this hinted to us that the linker may be to blame. Accordingly, we selected 1,3-propanediol as a linker motif as ester and ether linkers are common in the OROP literature.[14,24] Using the TMC-OPhF$_5$ synthon developed by Sanders and Hedrick,[30] our 1,3-propanediol linker was first coupled with ferrocenemethanol using catalytic Yb(OTf)$_3$.[31] Ferreocene ether **1** was then reacted with TMC-OPhF$_5$ and catalytic TBAF[32] to produce gram-scale quantities of ferrocene TMC monomer **2**. This synthetic procedure was next extended to the synthesis of ruthenocene TMC monomer **4**. Starting from ruthenocenecarboxylic acid,[33] LAH reduction, etherification with 1,3-propanediol and catalytic Yb(OTf)$_3$, and reaction of ruthenocene **3** with TMC-OPhF$_5$ efficiently produced ruthenocene TMC monomer **4**. Recrystallization was necessary for polymerization reactions and was accomplished by layering hexane on top of concentrated solutions of ethyl acetate. The structure of monomer **2** was confirmed by X-ray crystallography (ESI).



Scheme 2. Synthesis of ferrocene and ruthenocene TMC monomers.

Recent advances in organic catalysts for OROP suggested that polymerizations could be accomplished in seconds or minutes instead of hours or days.[34–36] Organic co-catalysts often include an H-bonding compound, such as a thiourea or a urea, and a strong base, such as a metal hydride, N-heterocyclic carbene (NHC), or 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). Organic catalyst combinations were screened for their speed and control using benzyl alcohol as an initiator and dichloromethane as the solvent. The percent conversions of the screening reactions were determined by ^{1}H NMR spectroscopy. The polycarbonate backbones and the 1,3-propanediol linker made the metallopolymer products fully soluble in tetrahydrofuran, enabling determination of molecular weights and dispersities by gel permeation chromatography with light scattering detectors (GPC-LS). Notably, GPC-LS was utilized because refractive index detectors (GPC-RI) calibrated to organic standards like polystyrene gave lower-than-expected molecular weights. This has also been observed for other metallopolymers with bulky functional groups pendant to the polymer backbone.[18,21]

It was found that when metal hydrides or NHCs were paired with a traditional thiourea catalyst (1-(3,5-bis(trifluoromethyl)phenyl)-3-cyclohexylthiourea, TU) or a urea (1,3-diphenylurea, DPU) at room temperature, the reaction of **2** was slow and/or gave a bimodal polymer distribution (ESI). Using the organic base DBU gave excellent polymerization results when paired with H-bonding catalysts TU (Table 1, entry 1) or DPU (entry 2), but reactions with DPU were faster and reached high conversion within 30 minutes. In addition, DPU is commercially available and inexpensive, which made it an ideal choice for the H-bonding catalyst. Using H-bonding catalyst DPU, monomer **2** was polymerized to high molecular weights with monomer:initiator ratios of 100 (entry 2) and 300 (entry 3), and monomer activation could be observed by ^{1}H NMR spectroscopy when DPU and **2** were mixed in equimolar ratios (Figure S21 in the ESI). The ruthenocene monomer **4** was also readily polymerized in 30 minutes using similar conditions (entry 4). The metallopolymer samples were conveniently purified by precipitation in water (typically homopolymers of **2**) or by dialysis against water (homopolymers of **4** and copolymers). High molecular weight shoulders were often observed in the GPC traces of the metallopolymers and were included in the molecular weight and dispersity calculations, but their impact on M_n and $Đ$ was minimal. In total, the reaction speed and metallopolymer size achieved with this method are unmatched for room-temperature metallopolymerizations.



Entry	*Monomer*	*Co-Catalysts (%)*	*Monomer: Initiator*	*Time (Conv)*	*Expected Mn (10^3)*[a]	*Actual M_n (10^3)*	*Đ*
1	**2**	TU(6%)/DBU(6%)	300:1	60 m (89%)	111	86	1.13
2	**2**	DPU(6%)/DBU(3%)	100:1	30 m (87%)	36	35	1.18
3	**2**	DPU(6%)/DBU(3%)	300:1	30 m (79%)	99	82	1.22
4	**4**	DPU(7%)/DBU(3%)	90:1	30 m (84%)	35	38	1.25

Table 1. Homopolymerization reactions of monomers **2** and **4** in dichloromethane using benzyl alcohol as an initiator. Molecular weights were measured using GPC-LS. [a]The expected molecular weights were scaled by the percent conversions of the monomers.

Two experiments were performed to gain insights into the mechanism of the polymerization. First, a chain extension experiment with ferrocene monomer **2** was attempted, with a starting monomer:initiator ratio of 150:1. After 30 minutes, a second portion of monomer **2** was added, making the monomer:initiator ratio = 300:1. The GPC traces showed that the additional monomer polymerized off of existing polymer chains and doubled the molecular weight (GPC-LS). In addition, a DOSY NMR spectrum of the extended product showed a single diffusion constant for all polymer resonances after the chain extension (Figure S47 in the ESI). The data from the chain extension experiment fit the profile of a living polymerization with active chain ends (Figure 1a).[34,37] In the second mechanistic experiment, the molecular weight of the polymer was plotted against the percent conversion of the ferrocene monomer **2** (Figure 1b). Aliquots were taken during the reaction and were analyzed by ^{1}H NMR spectroscopy to determine the percent conversions. Because of the presence of unreacted **2** in the aliquots, molecular weight calculations by GPC-LS were inaccurate and GPC-RI had to be used to estimate the molecular weights. Despite the low M_n values given by GPC-RI,[18,21] it was found that the GPC-RI values for the molecular weight of the metallopolymer increased linearly as a function of percent conversion, with an excellent R^2 value of 0.9992. The data also showed a first order dependence on the monomer concentration (Figure

S50 in the ESI). These results were all characteristic of a living polymerization and suggested that block copolymer synthesis was possible.[35]

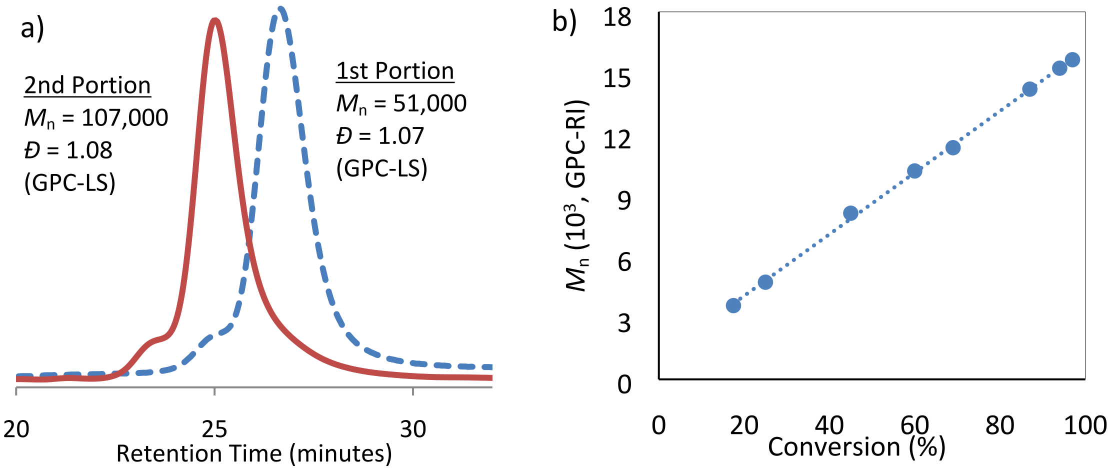
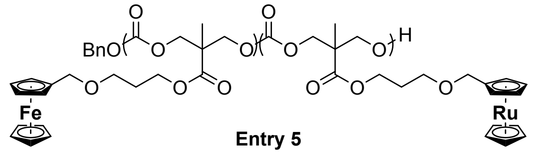
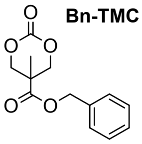


Figure 1. (a) A chain extension experiment using the monomer **2**. (b) The M_n tracked as a function of percent conversion during OROP of **2**.

The advantages of the OROP strategy were demonstrated by adapting the chain extension experiment for the one-pot synthesis of a heterobimetallic diblock copolymer using the monomers **2** and **4**. After a 30-minute polymerization of monomer **2**, monomer **4** was added and the reaction was quenched after 30 additional minutes of stirring (Table 2 Entry 5, **2**:**4**:Initiator = 100:100:1). The ^1H NMR spectrum revealed the expected polymer peaks, the GPC trace revealed a narrow peak at the expected molecular weight (M_n = 96,000, $Đ$ = 1.16), and DOSY confirmed that there was a single polymer product. Although some tapering of unreacted **2** into the second block is expected, our system's ability to prepare heterobimetallic diblock copolymers is noteworthy, as syntheses of these copolymers are rare.[12,16,21,27] For example, methacrylate polymers with pendant cobaltoceniums have been used as macroinitiators for the RAFT polymerization of methacrylates with pendant ferrocences, but the polymerization of the second block alone was performed at 90 ˚C for 5 hours or at 60 ˚C for 24 hours with a photocatalyst ($M_n \leq 72{,}000$).[16,27] By comparison, the largest main-chain examples were synthesized near room temperature (5 ˚C – 20 ˚C) by prolonged irradiation of ferrocenophanes and then cobaltocenophanes (20-48 hours, $M_n = 23{,}000 – 26{,}000$).[12]



Entry 5



Bn-TMC

Entry	*First Block (ratio)*	*Second Block (ratio)*	*Expected M_n (10^3)[a]*	*Actual M_n (10^3)*	*Đ*
5	**2** (100)	**4** (100)	83	96	1.16
6	**4** (145)	**Bn-TMC** (200)	106	93	1.13
7	**Bn-TMC** (200)	**4** (145)	109	115	1.11

Table 2. Diblock copolymers with monomers **2** and **4** using benzyl alcohol initiator. Molecular weights were measured by GPC-LS. All monomer blocks were reacted for 30 minutes in dichloromethane at room temperature. [a]The expected molecular weights were scaled by the percent conversions of the monomers.

Block copolymers with organic and metallic domains were also synthesized in a facile manner, suggesting that monomers **2** and **4** can be immediately integrated into functional biodegradable polymer syntheses with organic monomers compatible with OROP. For example, the ruthenocene monomer **4** was polymerized according to the standard conditions, and then a common organic cyclic carbonate with a pendant benzyl group (**Bn-TMC**) was added to the reaction mixture and stirred for an additional 30 minutes at room temperature. The ^{1}H NMR spectrum showed high conversion of each monomer and the GPC trace showed a narrow peak at the expected molecular weight (Table 2, entry 6). One could also select the order of the organic and metallic blocks. When the reaction was done in the reverse order (**Bn-TMC** then **4**, entry 7), an aliquot of the **Bn-TMC** block revealed 97% conversion after 30 minutes, and the organic polymer had the predicted molecular weight (expected M_n = 48,500; actual M_n = 48,000). After addition of **4** and 30 more minutes of stirring, the diblock copolymer had reached the expected molecular weight and had a low dispersity (expected M_n = 109,000; actual M_n = 115,000, $Đ$ = 1.11). Importantly, some tapering is to be expected in the diblock copolymer samples, as some unreacted monomer was present upon the addition of the second monomer. Nonetheless, the exquisite level of control and tolerance for the representative organic monomer **Bn-TMC** suggested that synthesis of a wide range of hybrid organic-metallic biodegradable polymers is possible.

In conclusion, a facile OROP strategy has been discovered that successfully bridges the fields of OROP and metallopolymers and enables the rapid synthesis of high-molecular weight metallopolymers at room temperature. The organic catalysts are inexpensive and the metallic monomers are compatible with a representative organic monomer for OROP. The new synthetic strategy is a significant advance in metallopolymer synthesis when the metal complex is pendant to the polymer backbone and has the potential to expand the scope of metallopolymer applications.

ASSOCIATED CONTENT

Electronic Supplementary Information (ESI) available: Experimental details, NMR spectra (^{1}H, ^{13}C, and DOSY), GPC spectra, the X-ray structure of **2**, and the mechanistic/kinetic experiments are available. See DOI: 10.1039/x0xx00000x

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Notes

The authors declare no competing financial interest.

AUTHOR CONTRIBUTIONS

Professors CRT and MT conceptualized the project. MT and his student investigators (ELW, CSJ, BSM, CMH, and CAH) synthesized all monomers. CRT and his student investigators (EER and YZ) synthesized and purified OROP catalysts, and other student investigators in CRT's group (KGO, KAW, JCL) completed the polymerizations.

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