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Synthesis of Telechelic Polyisoprene via Ring-Opening Metathesis Polymerization in the Presence of Chain Transfer Agent

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ABSTRACT: Telechelic polyisoprene was synthesized via the ring-opening metathesis polymerization (ROMP) of 1,5-dimethyl-1,5-cyclooctadiene (DMCOD) in the presence of *cis*-1,4-diacetoxy-2-butene as a chain transfer agent (CTA). This method afforded telechelic polymer in excellent yield, and the acetoxy groups were successfully removed to yield α,ω-hydroxy end-functionalized polyisoprene with potential for subsequent reactions. Efficient, quantitative incorporation of CTA was achieved, and NMR spectroscopy was utilized to confirm the chemical identity of the polymer end groups. Polymerization of discrete DMCOD monomer generated polyisoprene with excellent regioregularity in the polymer backbone. Successful ROMP of sterically challenging DMCOD in the presence of a CTA for chain end-functionalization was borne out through screening of a variety of Ru-based olefin metathesis catalysts.

Introduction

Ring-opening metathesis polymerization (ROMP) in the presence of a functionalized allylic olefin as a chain transfer agent has been successfully employed to synthesize telechelic polymers,[1] which are valuable commodities due to their versatility toward subsequent polymerization initiated from the chain ends to afford ABA triblock copolymers. ABA triblock copolymers have extensive utility for materials applications, including use in thermoplastic elastomeric films,[2] adhesives,[3] and biocompatible materials.[4] The center B-block of the ABA copolymer is commonly used to generate a material with desirable physical properties,[5] while A-blocks are often incorporated to render the material biocompatible or biodegradable.[6] In other cases, the A-blocks have been used to control the surface properties of the resulting macromolecules.[7] An advantage of using ROMP to construct a telechelic center B-block is that this methodology allows access to a wide range of polymer compositions and tolerates a broad scope of functionality. One class of monomers that has been underutilized in the synthesis of telechelic ROMP polymers are sterically encumbered, strained cyclic olefins, despite the fact that substituted cyclic olefins can give rise to a broad range of functional polymers. Specifically, ROMP of 1,5-dimethyl-1,5-cyclooctadiene (DMCOD) would generate, nominally, polyisoprene, a polymer of industrial potential [Scheme 1].

The potential of telechelic polyisoprene has attracted considerable attention due to the wide variety of commercial applications of this material. To date, the synthesis of telechelic polyisoprene has been primarily realized by reversible addition−fragmentation chain-transfer polymerization[8] or modification of natural rubber to functionalize the chain ends.[9] However, this method often requires harsh reaction conditions for functionalization.[10] Pilard and co-workers reported the synthesis of telechelic polyisoprene via degradation of natural rubber through Ru-mediated olefin metathesis in the presence of a functionalized allylic chain transfer agent.[11] The reported polydispersity indexes (PDI) of the obtained polymers were broad, indicating poor molecular weight control. This example highlights one of the most prominent inherent barriers for the synthesis of telechelic polyisoprene using ROMP—steric hindrance of the methyl substituted double bond significantly retards olefin metathesis during both polymerization and chain transfer events. ROMP of DMCOD in the presence of a CTA would provide a one-pot synthesis of telechelic polyisoprene with good molecular weight control, regioregularity in the polymer backbone, and a broad range of end-group functionalities. Recent advancements in Ru-based olefin metathesis catalysts were expected to provide new opportunities for the synthesis of telechelic polyisoprene by overcoming previous insufficiencies in catalyst activity.

Ruthenium metathesis catalysts have proven to be efficient initiators for ROMP of norbornenes and cyclooctadiene (COD) with a variety of chain transfer agents.[12] The ring-strain energy of metathesis substrates has been shown to significantly affect the monomer reactivity toward ring-opening metathesis, with strained substrates such as norbornenes exhibiting significantly enhanced reactivity over less strained COD. Trisubstituted olefins are traditionally challenging substrates for metathesis catalysts, with noticeably decreased reactivity compared to disubstituted olefins.[13] Collectively, DMCOD is a challenging ROMP substrate due to both the lower reactivity of the trisubstituted olefins and low ring-strain energy, rendering it significantly less reactive than previously reported monomers. Accordingly, a range of metathesis catalysts were explored to identify an effective system for the quantitative incorporation of CTA during polymerization of this challenging monomer. Herein, we report the one pot synthesis of telechelic polyisoprene from DMCOD monomer, with control over the final polymer molecular weight and well-defined microstructure.

Results and Discussion

Our studies commenced by comparing the activity of a series of known ruthenium metathesis catalysts (**1a**−**1g**, Figure 1) for the ROMP of trisubstituted DMCOD in the presence of *cis*-1,4-diacetoxy-2-butene (**2**) as the chain transfer agent (Scheme 2).

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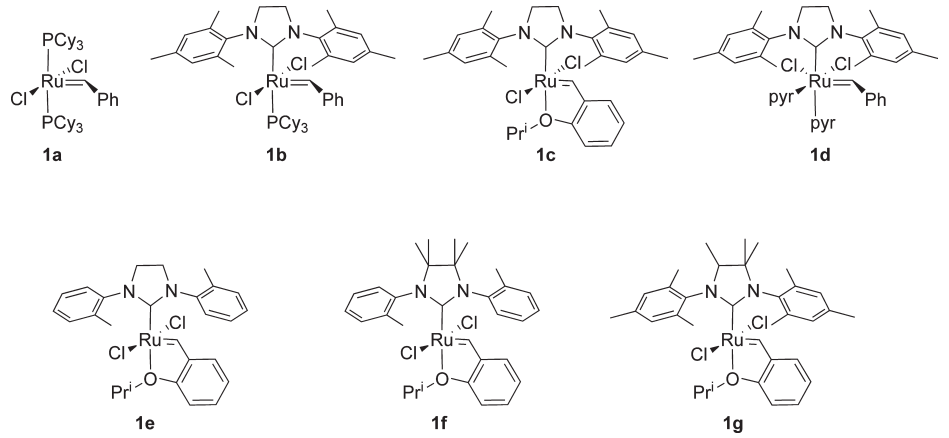
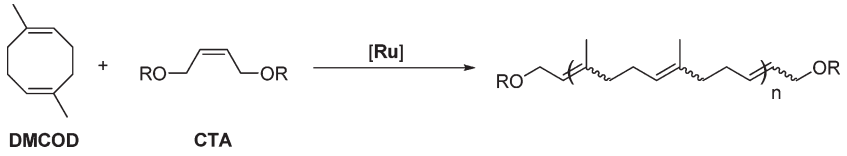
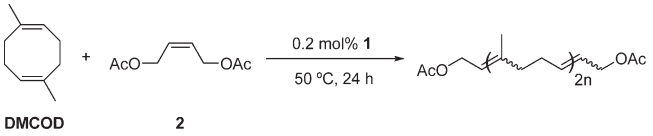


Figure 1. Ruthenium Catalysts Screened for ROMP of DMCOD with CTA.

Scheme 1. Synthesis of Telechelic Polyisoprene via ROMP of DMCOD with a Generic CTA



Scheme 2. Synthesis of α,ω-End-Functionalized Polyisoprene via ROMP



The ligand structure of ruthenium metathesis catalysts has been reported to significantly affect both activity and catalyst stability, and labile ligands have been shown to improve initiation, although often such complexes exhibit reduced catalyst lifetime.[14] A catalyst screen was therefore conducted to identify an efficient catalyst for rapid monomer polymerization and quantitative incorporation of chain transfer agent with this less reactive monomer. These attributes of the polymerization are essential for incorporating chain transfer agent on both ends of the polymer and for achieving molecular weight control. Accordingly, ruthenium catalysts representing a range of ligand substituents were chosen for polymerization screening to identify the ideal catalyst for optimal activity and stability (Figure 1). Catalyst stability and activity during the course of the polymerization is critical in producing difunctionalized polymer in high yield without monofunctionalized polymer impurity. Since DMCOD is a challenging ROMP substrate due to steric encumbrance of the trisubstituted olefins and has relatively low ring-strain energy compared to traditional ROMP monomers such as norbornenes, the identification of an active catalyst for the polymerization with equilibration of molecular weights with CTA presented a significant challenge.

First generation ruthenium metathesis catalyst **1a**, as well as those comprising N-heterocyclic carbene (NHC) ligands (**1b**−**1g**), were screened. Rigorously air-free conditions were required for high monomer conversion. Catalysts **1b**, **1c**, and **1d** were compared for initial rates as well as stability throughout the course of the polymerization. Sterics in the NHC backbone as well as substituents on the N-arene were evaluated for their impact on activity and stability. Complex **1a** did not polymerize DMCOD, despite being a successful initiator for the ROMP of COD (Table 1, entry 1).

Table 1. Catalyst Activity Screening for the ROMP of DMCOD in the Presence of CTA 2

entry[a]	catalyst[b]	% convn[c]	% yield	M_n(NMR)[d]	M_n(GPC)	M_w	PDI
1	**1a**	0	NA	NA	NA	NA	NA
2	**1b**	99	86	6620	9990	14 400	1.44
3	**1c**	85	74	6550	9650	13 100	1.39
4	**1d**	93	84	7680	10 700	15 100	1.40
5	**1e**	0	NA	NA	NA	NA	NA
6	**1f**	>99	85	7170	10 300	15 300	1.49
7	**1g**	73	64	6240	8330	11 600	1.40

[a] Polymerizations were conducted at 50 °C for 24 h. $[DMCOD]_0$ was 2 M in toluene. The molar ratio of DMCOD/**2** was 110/1. [b] Catalyst loading was 0.2 mol %. [c] Conversions were determined by ^{1}H NMR spectroscopy. [d] M_n was determined by ^{1}H NMR spectroscopy by relative integration of polymer chain-end olefin protons to internal olefin protons, assuming complete incorporation of **2**.

Catalyst **1b** exhibited good activity for the polymerization, reaching 99% conversion in 24 h (Table 1, entry 2). Catalysts **1c** and **1d** were also active, although complete consumption of monomer was not observed after 24 h (Table 1, entries 3 and 4, respectively). Interestingly, the less sterically hindered *N*-tolyl complex **1e** was found to be completely inactive for the polymerization of DMCOD (Table 1, entry 5). In contrast, backbone substitution on an *N*-tolyl complex (**1f**) resulted in excellent activity for the polymerization, giving greater than 99% conversion of monomer to polymer (Table 1, entry 6). Maintaining NHC backbone substitution while increasing the size of the *N*-aryl groups (**1g**) resulted in lower activity in comparison with the other active complexes (Table 1, entry 7). Collectively, the data confirm that smaller *N*-aryl groups are advantageous for activity, but that concurrent substitution on the NHC backbone is necessary for stability.[15]

Following these results, catalyst rates were compared by following conversion of DMCOD to polymer over time (Figure 2). The kinetics of the reactions were monitored by NMR spectroscopy. Catalyst **1g** was not evaluated as it was less active than the other complexes, reaching only 73% conversion in 24 h. Interestingly, whereas complex **1b** displayed the fastest initial rate, catalyst **1f**

reached 99% conversion in the shortest reaction time (12 h). Although complex **1d** has been reported to initiate olefin metathesis faster than **1b** or **1c**, **1d** was surprisingly slower than both **1b** and **1f** and comparable to **1c**, which is typically slower but more stable for metathesis reactions (Figure 2).[16] Considering the data from each of the catalysts, we focused our attention on complexes **1b** and **1f** as the most viable systems for accomplishing controlled synthesis of telechelic polyisoprene via ROMP.

The CTA was chosen as *cis*-1,4-diacetoxy-2-butene (**2**) since it can be easily deprotected to give hydroxyl groups, which could then be further reacted to make ABA block polymers. Allylic alcohols were not used directly as the chain transfer agent due to possible interference of the hydroxyl groups with the metathesis reaction. Hydroxyl groups are ideal end groups due to their flexibility for further functional group transformations, and their potential to be used directly as initiators in subsequent polymerizations.

The ratio of the initial concentration of CTA **2** to DMCOD was varied to yield telechelic polymer with a range of target molecular weights. The ability to control molecular weight by the ratio of $[DMCOD]_0/[\mathbf{2}]_0$ is an essential component of the method, allowing access to various polymer chain lengths for a number of applications. A study of molecular weight control was first carried out using catalyst **1b** since it is commercially available and relatively inexpensive (Table 2).

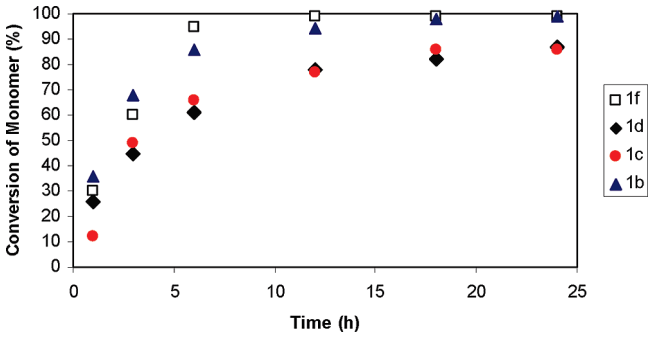


Figure 2. Conversion of DMCOD to polyisoprene versus time for complexes **1b**−**1d**, **1f**. Polymerization conditions: 0.2% **1**, 0.009 equiv of **2**, [DMCOD] = 2 M in toluene, 50 °C.

In accordance with our predictions, by varying $[DMCOD]_0/[\mathbf{2}]_0$, polymers with molecular weights ranging from 2000 to 25 000 g/mol were successfully synthesized. At high CTA loading, the conversion of DMCOD to polymer was lower (Table 2, entries 1 and 2), possibly due to greater catalyst decomposition. Control of polymer molecular weight with precise ratios of DMCOD to **2** was achieved (Table 2, entries 1−7). For high ratios of DMCOD to **2** targeting polymers of molecular weights greater than about 35 000 g/mol, the discrepancy between observed and theoretical molecular weight increased (for example, Table 2, entry 8).

Polymers exhibiting a range of target molecular weights were then synthesized with catalyst **1f** with the goal of increasing monomer conversion (Table 3). The conversion of DMCOD to polymer was complete for all reactions and the yields were significantly improved from complex **1b**.

The polymerization was successfully conducted on a larger scale to ensure practical synthesis. To this end, DMCOD (13 g) was polymerized in the presence of CTA **2** to afford acetoxy end-functionalized polyisoprene in 87% isolated yield. The polymer was subsequently deprotected to give hydroxy end-functionalized polymer in high yield (Scheme 3). The experimental molecular weight of α,ω-hydroxy functionalized polyisoprene (20 190 g/mol) closely matched the theoretical molecular weight of 20 050 g/mol.

The polyisoprene functionality (F_n) was determined to be 2 based on NMR spectroscopy (see Supporting Information). Two dimensional HSQC, HMBC, and DOSY were utilized to identify the presence of polymer acetate end groups, as well as demonstrate the absence of any terminal olefin groups or end

Table 2. Varying the Ratio of DMCOD to 2 with Complex 1b

entry[a]	$[DMCOD]_0/[2]_0$	% convn[b]	% yield	theoretical M_n (g/mol)[c]	M_n(NMR)[d]	M_n(GPC)	PDI
1	28	55	28	3800	1670	2440	1.22
2	56	77	51	7600	4220	6740	1.27
3	84	83	58	11 400	7120	10 700	1.28
4	110	86	56	15 000	8030	12 800	1.27
5	184	89	68	25 000	11 700	17 000	1.26
6	220	87	79	30 000	20 400	21 300	1.35
7	257	85	63	35 000	28 200	25 100	1.26
8	294	85	55	40 000	25 400	25 400	1.29

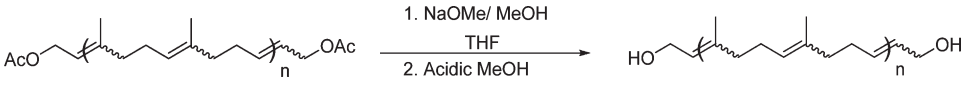
[a] Polymerizations were conducted at 50 °C for 20 h. $[DMCOD]_0$ was 2 M in toluene. The catalyst loading was 0.1 mol %. [b] Conversion was determined by ^{1}H NMR spectroscopy. [c] Assumes 100% conversion. [d] Determined by ^{1}H NMR spectroscopy by relative integration of the polymer chain-end olefin protons to the internal olefin protons, assuming complete incorporation of **2**.

Table 3. Varying the Ratio of DMCOD to 2 using Complex 1f

entry[a]	$[DMCOD]_0/[2]_0$	% convn[b]	% yield	theoretical M_n (g/mol)[c]	M_n(NMR)[d]	M_n(GPC)	PDI
1	50	98	80	6800	4130	6320	1.52
2	100	99	75	13 600	7550	10 600	1.63
3	150	99	76	20 400	11 200	18 100	1.43
4	200	>99	82	27 300	14 300	21 500	1.39
5	250	>99	80	34 100	15 300	24 200	1.39
6	500	>99	80	68 100	25 100	30 300	1.35

[a] Polymerizations were run at 50 °C for 15 h. $[DMCOD]_0$ was 2 M in toluene. The catalyst loading was 0.2 mol %. [b] Conversion was determined by ^{1}H NMR spectroscopy. [c] Assumes 100% conversion. [d] Determined by relative integration of the end group olefin protons compared to the internal polymer olefin protons, assuming complete incorporation of **2**.

Scheme 3. Hydroxy Telechelic Polyisoprene via Deprotection of Acetoxy End Groups



groups corresponding to the catalyst alkylidene initiator within the detection limits of the NMR spectrometer. The DOSY spectrum verified that all the signals except for $CDCl_3$ came from polymer. The presence of a methyl signal in the edited HSQC at 2.0/21.0 ppm was demonstrated to be the acetate methyl group by its HMBC correlation to the carbonyl carbon at 171 ppm; the methylene signal at 4.6 ppm correlates to the same carbonyl carbon. No terminal $=CH_2$ groups were observed in the HSQC. The absence of aryl signals in the ^{1}H NMR excluded any alkylidene initiator. Upon deprotection to afford hydroxy end groups, an upfield shift in the NMR signal was observed from 4.6 to 4.1 ppm for the terminal hydroxy CH_2. HMBC showed the disappearance of the acetate group.

Conclusion

We have successfully employed ring-opening metathesis polymerization of DMCOD in the presence of chain transfer agent for efficient one pot synthesis of telechelic α,ω-end functionalized polyisoprene. A series of ruthenium metathesis catalysts were screened, and viable complexes were identified that give good control of target molecular weights and afford polymer in excellent yields. This route is particularly attractive and advantageous in that the polymerization of a well-defined monomer (DMCOD) affords polyisoprene with controlled, defined polymer microstructure. The acetoxy groups were deprotected to give hydroxy end groups that can subsequently undergo a variety of reactions, rendering these telechelic polymers valuable precursors for the synthesis of triblock copolymers.

Experimental Section

General Considerations. All polymerizations were conducted under a nitrogen atmosphere using a drybox. ^{1}H and ^{13}C NMR spectra were recorded on a Varian Mercury (^{1}H, 300 MHz) or an automated Varian Inova 500 (^{1}H, 500 MHz; ^{13}C 125 MHz) spectrometer and referenced to residual protio solvent. HSQC, HMBC, and DOSY were carried out using a Varian Inova 600. Gel permeation chromatography (GPC) analyses were carried out in HPLC grade tetrahydrofuran on two PLgel 10 μm mixed-B LS columns (Polymer Laboratories) connected in series with a DAWN EOS multiangle laser light scattering (MALLS) detector and an Optilab DSP differential refractometer (both from Wyatt Technology). No calibration standards were used, and dn/dc values were obtained for each injection by assuming 100% mass elution from the columns.

Materials. Toluene was purified by passage through solvent purification systems. *cis*-1,2-Diacetoxy-2-butene was purchased from Aldrich and distilled over CaH_2 under Argon prior to use. 1,5-Dimethyl-1,5-cycloocatdiene was degassed by three freeze−pump−thaw cycles prior to use. Ruthenium complexes were received from Materia or synthesized according to published procedures.[17] All other reagents and solvents were used as purchased without further purification.

Representative Ring-Opening Metathesis Polymerization of 1,5-Dimethyl-1,5-Cyclooctadiene with *cis*-1,4-Diacetoxy-2-Butene as Chain Transfer Agent. In a nitrogen atmosphere glovebox, a 100 mL round-bottom flask containing a magnetic stir bar was charged with 1,5-dimethyl-1,5-cyclooctadiene (13.19 g, 96.8 mmol). Toluene (16 mL) was then added and the solution was stirred at 22 °C. Catalyst **1b** (0.082 g, 0.1 mol %) was added to the flask with stirring, after which *cis*-1,4-diacetoxy-2-butene (105 μL, 0.0068 equiv relative to DMCOD) was added via syringe. The round-bottom flask was sealed with a glass stopper in the glovebox and then brought out and heated to 50 °C in an oil bath for 24 h. An aliquot was taken out by syringe for ^{1}H NMR spectroscopy and the conversion to polymer was determined to be 92% by relative integration of the olefin peaks. The polymerization was terminated by the addition of ethyl vinyl ether (2 mL), and the polymer was precipitated by dropwise addition into 175 mL of anhydrous methanol. The supernatant was decanted, and the polymer residue was washed twice more with methanol. The polymer was then redissolved in 50 mL of toluene and slowly added via an addition funnel to 400 mL of methanol with stirring. The methanol solution was again decanted off, and the resulting polymer was dried under vacuum on a Schlenk manifold for 48 h. The polymer was isolated in 87% yield (11.44 g). ^{1}H NMR ($CDCl_3$, 500 MHz): δ 5.10−5.13 (m, 2H), 2.00−2.06 (br, m, 8H), 1.68 (br, s, 3H), 1.59−1.60 (br, m, 3H) ppm. Acetate end groups: CH_2 4.55−4.60 ppm, CH_3 2.0 ppm. The polymer end groups contained both *cis* and *trans* isomers. ^{13}C NMR ($CDCl_3$, 125 MHz): δ 135.1, 125.1, 124.2, 40.1, 39.8, 32.2, 32.0, 26.5, 23.5, 16.0 ppm.

Representative Deprotection of Polymer Acetate End Groups. α,ω-Diacetoxy polyisoprene (10.28 g) was dissolved in 100 mL of THF and cooled to 0 °C in an ice bath. A 25 wt % solution of NaOMe in methanol (15 mL) was added slowly and the mixture was stirred for 72 h at 22 °C. The reaction mixture was then added dropwise via an addition funnel into 600 mL of acidic methanol (0.5 mL of concentrated HCl in 600 mL of anhydrous methanol). The acidic methanol solution was decanted off, and the precipitate was washed three more times with acidic methanol, followed by washing three times with a 1:1 methanol/water solution. The polymer was subsequently washed three times with anhydrous methanol, then dried under vacuum using a Schlenk manifold for 48 h. The polymer (9.10 g) was isolated in 89% yield. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 5.12−5.13 (m, 2H), 1.98−2.05 (br, m, 8H), 1.69 (br, s, 3H), 1.60−1.61 (br, m, 3H) ppm. Hydroxy end groups: CH_2 4.05−4.15 ppm. The polymer end groups contained both *cis* and *trans* isomers. ^{13}C NMR ($CDCl_3$, 125 MHz): δ 135.1, 125.1, 124.3, 40.1, 39.8, 32.2, 32.0, 26.6, 26.5, 26.4, 23.5, 16.0 ppm.

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Supporting Information Available: Figures showing NMR spectra for polyisoprene with both acetoxy and hydroxy functionalized end groups. This material is available free of charge via the Internet at http://pubs.acs.org.

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