

Cascade ring opening/ring closing metathesis polymerization of a monomer containing a norbornene and a cyclohexene ring

Mohammad Yasir and Andreas F. M. Kilbinger*

Department of Chemistry, University of Fribourg, Chemin du Musée 9, CH-1700 Fribourg, Switzerland

Supporting Information Placeholder

ABSTRACT: Norbornene is polymerized extremely fast when reacted with Grubbs' first (**G1**) or third generation catalyst (**G3**) because of its very high ring strain energy. Cyclohexene, on the other hand, cannot be polymerized using **G1** or **G3** due to its very low ring strain energy. Subsequently, the sequence selective polymerization of these two monomers is extremely challenging. A sequence selective cascade ring opening/ring closing metathesis polymerization of the monomer **M** containing both, the norbornene and the cyclohexene ring using **G1** or **G3** is reported. The polymer structure was analyzed by ¹H NMR, ¹H-¹H COSY and ¹H-¹H ROESY spectroscopy and MALDI-ToF mass spectrometry. Polymers with moderate molecular weight dispersities and good molecular weight control were achieved by varying the ratio between monomer **M** and **G1**.

Controlling the monomer sequence in an alternating fashion is challenging. The combination of specially designed monomers has given access to alternating polymers. Such polymers are most often synthesized by radical polymerization.^{1,2,3,4} Achieving the synthesis of strictly alternating polymers by ring opening metathesis polymerization (ROMP) is challenging in comparison. There are several reports of alternating ROMP. Xia and coworkers, for example, have recently developed an interesting strategy based on single additions of cyclopropene derivatives in combination with cyclopentene or cyclohexene to yield living alternating copolymers.⁵ Sampson's group produced alternating copolymers from a mixture of cyclobutene-1-carboxylic esters or amides and cyclohexene derivatives.^{6,7,8,9,10} Alternating ROMP typically involves a pair of cyclic monomers where one is hindered and strained while the other is unhindered and only slightly strained.^{5,11} Alternatively, the combination of a strained monomer carrying an electron-deficient double bond with a monomer showing less ring strain but carrying a more electron-rich double bond has also allowed the synthesis of alternating ROMP polymers.^{6,7,8,9,10,12} Grubbs et al. controlled the alternation via equilibration in ring opening insertion metathesis polymerization (ROIMP).¹³ Moreover, different metathesis catalyst designs were used to achieve alternating polymerization.^{14,15,16,17}

Sequence selective cascade metathesis reactions have mainly been used for the synthesis of organic molecules and functional catalysts.^{18,19,20,21,22,23} However, few of such reactions have also been explored in polymer synthesis. Choi and coworkers reported an elegant strategy

allowing polymerization of alkyne and cyclohexene functional groups present within a single monomer in an alternating manner via a tandem ring opening/ring closing metathesis (RO/RCM) reaction.^{24,25,26} There, the alkyne is an example of a slowly homo-propagating monomer and cyclohexene an example of a monomer with very low ring strain (1.6 kcal/mol).²⁷

Conceptually similar to the above example is an interesting monomer containing both a cyclopentene and a cyclohexene ring which has been designed by the same group to achieve a sequence selective cascade RO/RCM polymerization (Scheme 1b).²⁸ The ring strain energy of cyclopentene is 5.9 kcal/mol²⁷ with a difference in both ring strain energies of 4.3 kcal/mol. For such a combination of cycloalkenes both cross-propagation reactions are favored and a sequence controlled alternating polymerization is, therefore, more likely to occur. It is also important to note that the polymers obtained featured broad molecular weight dispersities and only low molecular weight control.

Recently, a living polymerization combining olefin metathesis and a metallotropic shift occurring in an alternating cascade manner was also reported by the same group.²⁹ There are numerous reports showing interesting cascade cyclopolymerizations of monomers containing alkyne functional groups to produce conjugated polymers using ruthenium-^{30,31} and molybdenum-based catalysts.^{32,33,34,35,36,37} Choi et al. showed a mechanistically unique cascade RO/RCM polymerization of a monomer containing two cyclopentene fragments using **G1** (dichloro(benzylidene)bis(tricyclohexylphosphine) ruthenium(II)) (Scheme 1a).^{38,39} However, this reaction strategy naturally lacks the sequence selectivity due to the presence of two identical rings.

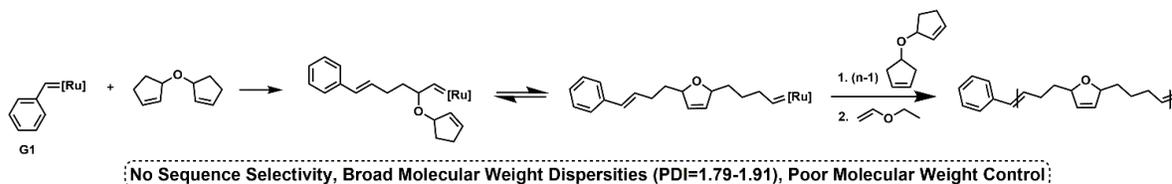
Norbornene and its derivatives, on the other hand, are examples of monomers that have very high ring strain (27.2 kcal/mol)²⁷ and hence propagate extremely rapidly using the **G1** initiator. In contrast, cyclohexene cannot be polymerized at all using **G1** due to its very low ring strain energy (v. supra). A sequence selective polymerization of these two monomers could therefore be considered particularly challenging.

Here, we describe the synthesis and polymerization of monomer **M** (7-(cyclohex-2-en-1-yloxy)bicyclo[2.2.1]hept-2-ene) containing both, a norbornene and a cyclohexene fragment.

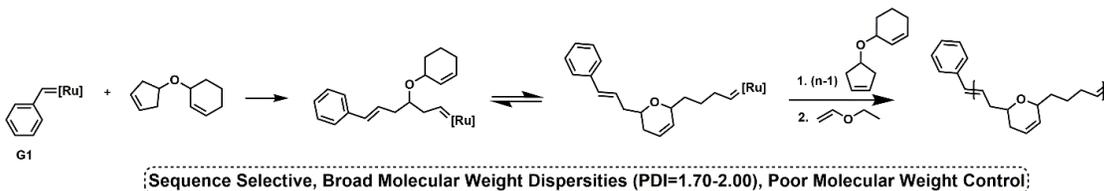
To our initial surprise, this monomer underwent a cascade RO/RCM polymerization in a sequence selective manner using **G1** (Scheme 1c). Polymers with good molecular weight control and narrow molecular weight dispersities were obtained in short reaction times.

Scheme 1. Cascade RO/RCM polymerization of the monomers containing similar/different reactivity fragments.

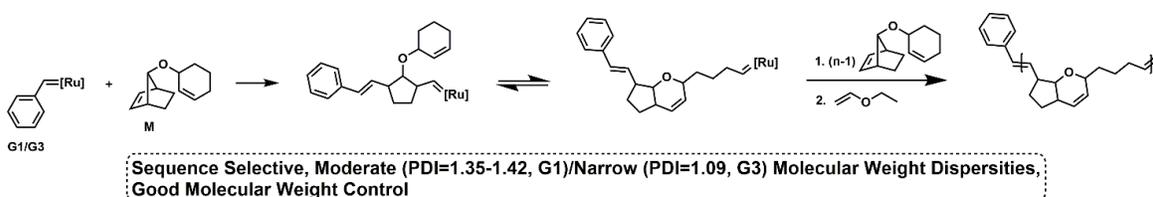
(a) Choi-2015, 2018:



(b) Choi-2018:



(c) This work:



Monomer **M** (15 eq.) was reacted with **G1** (1 eq.) and the reaction was followed by ^1H nuclear magnetic resonance (NMR) spectroscopy (entry 1, Table S1, Supporting Information). First, the norbornene fragment which is more reactive undergoes a ring opening metathesis reaction to form a new ruthenium carbene complex. This newly-formed complex then reacts with the cyclohexene fragment in a ring closing-ring-opening sequence to form a thermodynamically stable six-membered cyclopenta-pyran derivative (Figure 1b). Despite the vast differ-

ence in ring strain energies, the intramolecular ring-closing reaction appears to be favored over a homo-propagation of the norbornene fragments. In this manner, the norbornene and cyclohexene fragments of the monomer **M** were polymerized in an alternating fashion.

We believe that the ruthenium complex formed after ring-opening of the norbornene derivative is sterically very crowded. After the additional ring-closing reaction with the easily accessible cyclohexene ring a less crowded carbene complex is formed.

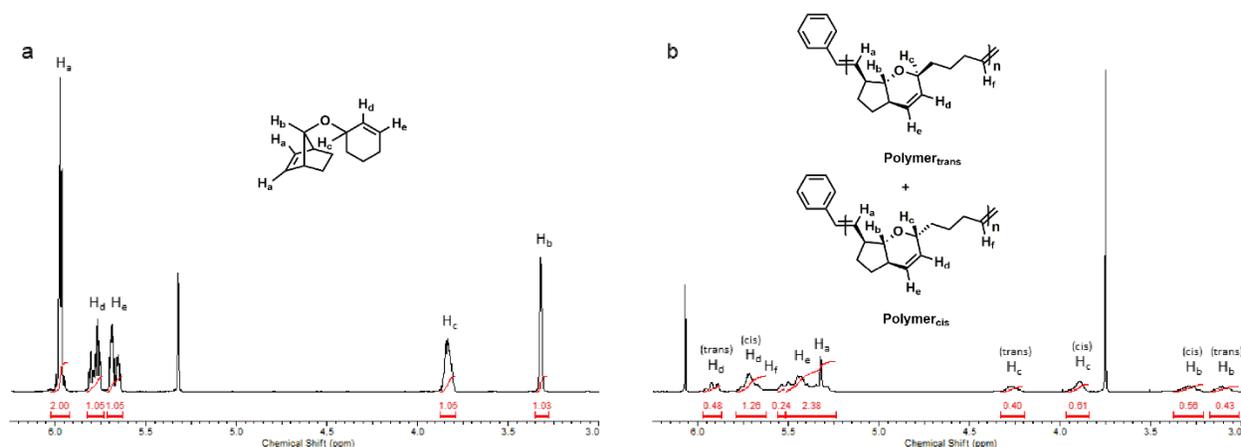


Figure 1. ^1H NMR spectra (300 MHz, CD_2Cl_2) of (a) monomer **M** and (b) polymer, signals at 3.75 and 6.07 ppm belong to the aromatic and methoxy protons of the internal standard i.e. 1,3,5 trimethoxybenzene.

The different propagation kinetics of these two carbene complexes could be the reason that we exclusively observe a strictly RO/RCM polymer. This explanation is in line with the Curtin-Hammett principle,⁴⁰ i.e. for a reaction that has a pair of reactive intermediates that interconvert rapidly,

each going irreversibly to a different product, the product ratio will depend on the difference in energy between the two rapidly interconverting reactive intermediates. In other words, the more reactive intermediate will determine the final product.

The norbornene (5.98-5.96 ppm, Figure 1a) and cyclohexene olefinic protons (5.81-5.75, 5.70-5.64 ppm, Figure 1a) disappear within 12 min to yield the RO/RCM polymer (Figure 1b). Had the polymerization not proceeded through the RO/RCM reaction, a predominant or possibly exclusive disappearance of the norbornene signals would have been expected as the cyclohexene rings cannot undergo homo-polymerization using **G1**. Further support for the RO/RCM polymerization can be obtained from the ¹H NMR spectrum (see Figure S5, S6, Supporting Information) of the RO/RCM polymer **P1**, in particular the proton signals for H_b and H_g. Assuming the reaction product was a mixture of RO/RCM-polymer and RO-polymer, it would be unlikely that the ratio of the signal intensities for H_b and H_g would be exactly 1:1. Both, H_b and H_g would be identical in a hypothetical RO-polymer. Thus, the mechanism shown in Scheme 1c can be elucidated by the exclusive presence of the RO/RCM polymer structure in the reaction product.

In order to determine the minimum time required for polymerization two further reactions similar to the one reported above were run and terminated with 0.1 mL (215 eq) of ethyl vinyl ether (EVE) after 4 and 6 min. ¹H NMR spectroscopy revealed 97% (4 min.) and 100% (**P1**, 6 min., M_n=4200 g mol⁻¹, Đ=1.35) monomer conversion (Table S1, Supporting Information). The structure of **P1** was analyzed by ¹H NMR spectroscopy (Figure S5, Supporting Information).

The ¹H NMR spectrum of **P1** is complicated by the presence of four stereogenic centers resulting in two diastereomers and additional E/Z isomerism of the acyclic olefin per repeat unit (Figure 1 b). We believe that the observation of two sets of ¹H-NMR peaks for the protons H_b, H_c and H_d is further support for the formation of two types of rigid bicyclic repeat units (called Polymer_{trans} and Polymer_{cis} in Figure 1b) which can only be formed by the ring-opening-ring-closing cascade reaction.

The peak assignment shown in Figure 1b is based on further NMR spectra obtained by ¹H-¹H correlation spectroscopy (COSY, Figure S6, Supporting Information) and ¹H-¹H rotating frame nuclear Overhauser effect spectroscopy (ROESY, Figure S7, Supporting Information). Furthermore, the ¹H NMR spectrum of **P1** agrees with that of a compound similar to the one shown in Figure 1b which was reported previously.²⁷

In addition, size exclusion chromatography SEC (THF) and isotopically resolved matrix-assisted laser desorption ionization time of flight mass spectrometry (MALDI-ToF MS) confirmed the expected polymer (Figures S2a and S9, Supporting Information).

Subsequently, polymers (**P2** and **P3**) of a differing molecular weight were synthesized by varying the monomer **M** to **G1** ratio (20:1 and 25:1) (Table 1). Good molecular weight control was observed. The molecular weight dispersities of the polymers were moderate and within the expected range for **G1** initiated living polymerizations. This clearly shows that the cyclic and acyclic double bonds present in the polymer backbone do not readily undergo chain transfer events.²⁷

Finally, we used a highly active catalyst i.e. Grubbs' third generation catalyst (**G3**) for this polymerization. When monomer **M** (15 eq) was reacted with **G3** (1 eq), a narrow molecular weight dispersity and controlled molecular weight polymer **P4** (Đ=1.09, M_n=2.9 g mol⁻¹, Table 1) was formed. The ¹H NMR spectrum (Figure S8, Supporting Information) of **P4** was identical to that of **P1** indicating that both polymerization initiators, **G1** and **G3** polymerized monomer **M** via the same mechanism.

Table 1. Synthesis of polymers of a differing molecular weight by varying the monomer M to G1 ratio. The amount of the catalyst (4

mg, 0.00486 mmol, 1 eq) and concentration of the monomer (0.081 M) were kept constant.

M:G1/G3	time (min)	conv. ^a	M _n , theo ^b (kDa)	M _n , found ^c (kDa)	Đ ^c	yield	
15:1/-	6	100%	3.7	4.2	1.35	85%	P1
20:1/-	8	100%	4.9	5.3	1.42	88%	P2
25:1/-	10	100%	6.1	6.3	1.40	90%	P3
15 :-/1	1	100%	2.9	2.9	1.09	86%	P4

^aConversion was determined via ¹H NMR spectroscopy. ^bTheoretical molecular weight was calculated according to 72% initiation efficiency of **G1** (Figure S1, Supporting Information) except for **P4** (in case of G3, as it is known for complete initiation). ^cMolecular weight and polydispersity index (PDI (Đ)) were determined using tetrahydrofuran (THF) size exclusion chromatography (SEC) (Figure S2, Supporting Information).

In conclusion, a monomer **M** containing two unsaturated rings of extremely different ring-strain i.e. norbornene and cyclohexene was synthesized. When this monomer was initiated with Grubbs' 1st generation initiator **G1**, it yielded polymers via a sequence selective cascade RO/RCM reaction. This shows that in this case the significantly less reactive cyclohexene reacts faster in an intramolecular reaction than the reactive norbornene in a hypothetical intermolecular homo-propagation reaction. The structure of the polymer was analyzed by ¹H NMR spectroscopy, ¹H-¹H COSY, ¹H-¹H ROESY and MALDI-ToF MS. The variation of the ratio between monomer **M** and **G1** allowed the synthesis of polymers with controlled molecular weight and moderate molecular weight dispersities. This cascade polymerization was also carried out with a highly active catalyst **G3** which yielded a narrow molecular weight dispersity and controlled molecular weight polymer via the same polymerization mechanism.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental methods, SEC data, NMR spectra, MALDI-ToF data (PDF)

AUTHOR INFORMATION

Corresponding Author

*andreas.kilbinger@unifr.ch

ORCID

Andreas F. M. Kilbinger: 0000-0002-2929-7499

Notes

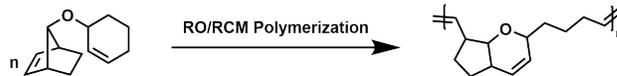
The authors declare no competing financial interests.

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