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Cyclodimerization of Alkynes with Phosphine-Free Ruthenium Carbene Complexes: Carbene Consumption by a Shunted Alkyne Oligomerization

Steven T. Diver,* Amol A. Kulkarni, Daniel A. Clark, and Brian P. Peppers

Department of Chemistry, University at Buffalo, the State University of New York, Buffalo, New York 14260-3000

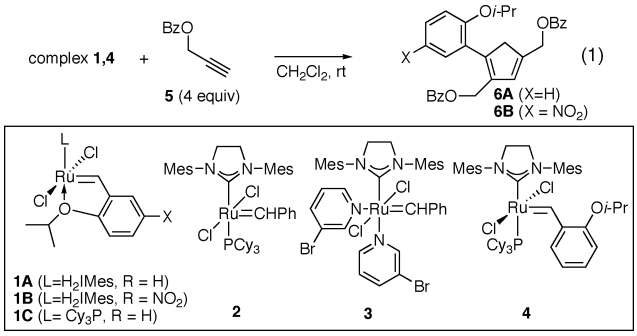
Received January 25, 2007; E-mail: diver@buffalo.edu

Metathesis promoted by the Grubbs carbenes has become an important method for the synthesis of alkenes and dienes.[1] Despite this fact, there have been comparatively few studies on the decomposition of metathesis-active ruthenium carbene complexes.[2] Decomposition of metal carbenes is of fundamental interest, and an improved understanding of the decomposition processes of these important catalysts will ultimately lead to more efficient catalysts. In this Communication, we report a new ruthenium carbene-mediated reaction pathway found to be operating under catalytic enyne metathesis conditions. The new pathway results in the formation of cyclopentadienes by two successive alkyne insertions into the metal carbene (Scheme 1). Since the cyclodimerization occurs off the alkyne oligomerization pathway, we refer to this reaction as a shunted oligomerization.

Decomposition through cyclodimerization depends on two partitioning steps of ruthenium vinyl carbenes. Mechanistic inquiry in enyne metathesis has asked which reacts first, the alkyne or the alkene. This same question can be applied to the catalytic intermediate **A**, a vinyl carbene. The vinyl carbene intermediate lies at a nexus, as it can bind and react with alkenes or alkynes,[3] leading to either enyne metathesis or alkyne oligomerization,[4] respectively. Normally, enyne metathesis occurs on the top fork of Scheme 2 since excess alkene is present; mechanistic studies support that higher alkene concentration promotes catalytic turnover.[3a−c] When alkene concentration is low, alkyne oligomerization may take place via the bottom fork of Scheme 2. In this case, terminal alkyne binding and insertion leads to a second vinyl carbene **B** with a new branchpoint. Here additional alkyne insertion may occur giving the oligomer (path a), or a cyclization process may occur giving the cyclopentadiene (path b). In the cyclodimerization (path b), the metal fragment is lost, resulting in carbene consumption (details below). The observed cyclodimerization is significant because this unique reactivity profile to form cyclopentadiene **C** provides direct evidence of a competing process for enyne metathesis. Second, the cyclodimerization suggests a new metal carbene decomposition pathway, which has implications for catalysis and the way enyne metatheses should be conducted.

Cyclodimerization was observed using phosphine-free carbene complexes with coordinating ethers. The cyclopentadiene product was observed under catalytic conditions during an attempted cross enyne metathesis between alkyne **5** and excess methyl vinyl ketone (MVK). The cross metathesis failed, and the cyclopentadiene **6A** was isolated instead (eq 1 in Scheme 1 and Table 1). Leaving the alkene out completely gave a 49% yield of the cyclopentadiene **6A** (entry 2). Similarly, the Grela complex **1B** produced the corresponding cyclopentadiene in comparable yield (entry 3). Interestingly, the Grubbs complex **2** did not produce any isolable cyclopentadienes (entry 4).[5] The phosphine-free Grubbs pyridine solvate **3** gave results similar to that found in entry 4. The first generation Hoveyda complex **1C** produced **6A** (entry 6), albeit more slowly (12−20 h, excess alkyne) than with complex **1A**. Use of

Scheme 1. Cyclopentadiene Formation



Scheme 2. Enyne Metathesis versus Alkyne Polymerization and the Shunted Alkyne Polymerization (path b)

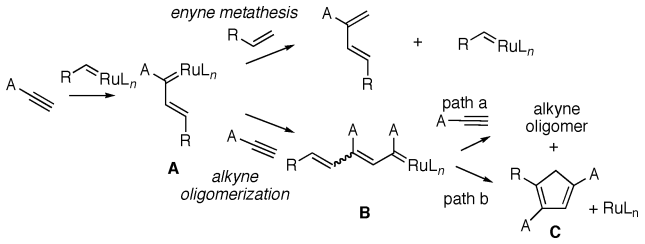


Table 1. Cyclopentadiene Formation (eq 1, Scheme 1)

entry[a]	complex (1 equiv)	alkene	**6**, yield[b,c]
1	**1A**	MVK, 60 mM	**6A**, 35%[d]
2	**1A**	none	**6A**, 49% (53%)[e]
3	**1B**	none	**6B**, 39%
4	**2**	none	<5%
5	**3**	none	<5%
6	**1C**	none	**6A**, 37%[f]
7	**1A**, Ph_3P (1:1)	none	**6A**, 32%
8	**4**	none	**6A**, 31%

[a] Conditions: metal complex **1**−**4** (5 mM), alkyne **5** (20 mM), CH_2Cl_2, rt, 1−24 h. Unless otherwise noted, all carbene complex and alkyne were consumed. [b] Yield is based on carbene complex. [c] NMR yield versus internal standard. [d] Isolated. [e] Repurified complex **1A** gave 53% **6A**. [f] 18% recovered **1C**.

1A with Ph_3P or use of the preformed Blechert complex **4** gave a reduced yield of **6A** (entries 7 and 8). From these data, the presence of coordinating ether on the benzylidene moiety is required to obtain the cyclized product.

Cyclopentadienes were produced under nominal conditions of enyne metathesis (Table 2). Cyclopentadiene production is associated with carbene decomposition and might explain why high loadings are needed in some cases. Typical enyne cross metatheses use an excess of alkene.[6] Mechanistic studies[3a] suggest that excess alkene is needed to turn over the vinyl carbene intermediate. In a typical enyne metathesis between alkyne and 1-hexene, we observed the yields of metathesis product and cyclopentadiene. At lower

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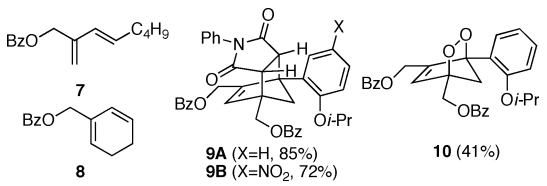
Table 2. Cyclodimerization Observed under Nominal Metathesis Conditions

entry[a]	alkene	**6A**, yield[b,c]	diene yield[b,d]
1	1-hexene, 20 mM	10%	**7**, 29%
2	1-hexene, 40 mM	4%	**7**, 40%
3	1-hexene, 60 mM	nd[e]	**7**, 51%
4	1,5-COD, 20 mM	20%	**8**, 30%
5	1,5-COD, 40 mM	12%	**8**, 40%
6	1,5-COD, 60 mM	8%	**8**, 55%

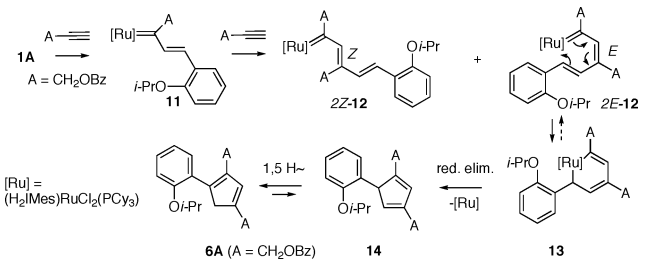
[a] Conditions: **1A** (1 equiv, 5 mM), alkyne **5** (20 mM, 4 equiv), CH_2Cl_2, rt, 24 h. All reactions went to complete conversion of alkyne **5**. [b] Average of two runs. [c] Determined by ^{1}H NMR; yield is based on carbene complex. [d] Determined by ^{1}H NMR; yield is based on the alkyne. [e] Not detected.

alkene concentrations, evidence of competing reactions was expected. At 1 equiv of 1-hexene (entry 1), the cyclopentadiene **6A** was detected in 10% yield.[7] As the 1-hexene concentration was increased, the cyclopentadiene yield dropped with a concomitant increase in the yield of 1,3-diene (entries 2 and 3). Next we probed whether the cyclodimerization occurred during a more difficult metathesis. We previously developed conditions for cyclohexadiene ring synthesis (e.g., **8**) by "methylene-free" enyne metathesis using 1,5-cyclooctadiene (COD).[8] The success of the methylene-free ring synthesis was dependent on COD concentration. We hypothesized that a slow vinyl carbene turnover step could lead to competitive pathways, including metal carbene decomposition. To test this, we examined the methylene-free conditions at different concentrations of alkene (entries 4−6). With 1 equiv of COD, the cyclopentadiene **6A** and cyclohexadiene **8** were produced (entry 4). Increased concentration of COD increased the ratio of the cross metathesis product **8** to the cyclodimerization product (entries 5 and 6). Under the appropriate conditions, cyclopentadiene formation, and hence carbene decomposition, can be effectively suppressed.



The substitution pattern on the cyclopentadiene substructure was established through NOE studies and cycloadduct formation. NOE studies of **6A** established the proximity of the vinylic proton with both benzoyloxymethylene groups, supporting the 1,3-disposition of the alkyne substituents.[9] The cyclopentadienes were trapped to give the corresponding cycloadducts **9** and **10**. Reaction of **1A** with other 1-alkynes produced cyclopentadienes as tautomeric mixtures.[10]

Scheme 3. Proposed Mechanism of Alkyne Cyclodimerization



The proposed mechanism of the carbene-promoted alkyne cyclodimerization is illustrated in Scheme 3. Vinyl carbene formation is followed by alkyne binding with the generation of isomeric vinyl carbenes **12**. Electrocyclization of (2*E*)-**12** would access the ruthenacyclohexadienes **13**, which would suffer reductive elimination[11] to give a cyclopentadiene **14**. With regard to catalytic enyne metatheses, the cyclopentadiene formation step *consumes* the carbene complex by a process that has not been previously observed for the Grubbs' carbenes. Facile 1,5-hydride shift[12] would produce observed tautomer **6A**. The modest yields of cyclopentadienes can be explained by the many competing reactions, including those promoted by the ruthenium(II) byproduct. The aryl ether moiety on the carbene appears to be critical to producing the cyclopentadiene by cyclodimerization.

In summary, a new alkyne cyclodimerization has been observed under conditions of enyne metathesis. The addition of a second alkyne to a vinyl carbene intermediate suggests partitioning between enyne metathesis and alkyne oligomerization. From kinetic studies, we previously found that higher alkene concentration accelerates the rate of enyne metathesis. Higher alkene concentration improves catalytic efficiency by accelerating vinyl carbene turnover and by minimizing carbene decomposition possible through the cyclodimerization process. Further mechanistic studies are in progress.

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Supporting Information Available: Experimental procedures and characterization data for **6**, **9**, and**10**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(5) In the crude ^{1}H NMR, there was less than 5% (vs internal standard) of what was tentatively assigned as cyclopentadienes (CH_2 resonance at δ 3.6 ppm). Efforts to isolate this from the oligomeric mixture proved fruitless.

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(7) In these entries, the balance of the mass is assumed to be polymer.

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(9) See Supporting Information for further details.

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