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Structure and Reactivity of Alkynyl Ruthenium Alkylidenes

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Abstract

The isolation and structural characterization of alkynyl Ru-alkylidene species has been elusive due to their rapid metallotropic shift and fast turnover. The enyne ring-closing metathesis and relay metathesis provides the platform to form a variety of alkynyl Ru-alkylidene species possessing sterically and electronically different substituent on the carbenic carbon, which allowed their regio-controlled trapping and structural characterization.

The stability and reactivity of Grubbs-type ruthenium complexes have been shown to be critically dependent on the nature of ligands on the metal and the substituents on the carbenic carbon.¹ The reactivity of Ru-methylidene (**1**)^{1a,b} and its alkyl-(**2**),^{1a,b} vinyl (**3**),^{1c} and phenyl-substituted (**4**)^{1a,b,d} versions as well as the Hoveyda-type chelate (**5**) and its variants² are extensively studied and utilized in organic synthesis and polymer chemistry.³ However, to the best of our knowledge, little is known about the structure and reactivity of alkyne-substituted Ru-alkylidenes (**6**).⁴ A part of this discrepancy could be due to the lack of efficient methods for their preparation although several reported metathesis processes may involve the alkynyl Ru-alkylidene species as an intermediate.⁵ In the enyne ring-closing metathesis of diyne- or triyne-containing substrates, putative alkynyl Ru-alkylidene species have been formed, however, due to their rapid metallotropic [1,3]-shift⁶ and subsequent turnover, the isolation and structural characterization of these intermediates has been elusive. At this juncture, we surmised that the equilibrating alkylidenes **A–C** could be selectively trapped and fully characterized if suitable electronic and steric constraints of R and R' substituents are met (Eq 1). In this *Communication* we report the reactivity features of equilibrating Ru-alkynyl alkylidenes and their first X-ray structure-based characterization in the form of Grubbs-type and Hoveyda-type complexes.

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(1)

First, the substituent effect was examined with triynes **7a–e**,⁷ which showed that both steric and electronic factors at the terminating end have a profound impact on the product distribution (Scheme 1). With Grubbs second-generation catalyst **4b**, substrate **7a** with an acetoxysubstituted alkyl group gave diyne **8a** (82%) whereas simple alkyl substituted triyne **7b** gave a mixture of **8b** (34%) and **8b'** (41%). Triethyl silyl and *t*-butyl substituted triynes **7c**⁶ and **7d** provided exclusively **8c** (79%) and **8d** (73%). Surprisingly, terminal triyne **7e** ($R = H$) did not undergo catalytic turnover but afforded **8e** in 62% yield when a stoichiometric amount of **4b** was used.⁸ Similarly, diyne **9**⁹ provided complexes **10a** (93%) and **10b** (79%) with stoichiometric amounts of **4a** and **4b**, respectively. The X-ray structures of **10a** and **10b** show a typical arrangement of ligands around the metal center without having any extra interaction of the attached alkyne moiety to the metal.^{8,10} These results clearly indicate that the important role of steric hindrance at the terminal position in generating alkylidene **A** and **C**. The lack of formation of products derived from Ru-alkylidene **B** in these reactions is less likely due to the steric hindrance of dialkynyl groups but more due to its less favorable electronic environment: cross-conjugation and the presence of two electron-withdrawing alkynyl substituents on the carbenic carbon. On the other hand, the particular stability (low reactivity) of alkynyl alkylidenes **8e** and **10a,b** is assumed to be the consequence of a low steric pressure exerted by the alkyne moiety in combination with that of the hydrogen on the carbenic carbon. Thus, once rebound to form a catalyst resting state, the dissociation of tricyclohexyl phosphine ligand from **8e** and **10a,b** would become more difficult compared to that of the corresponding alkyl substituted alkylidenes.¹¹

To gain more insight into the influence of substituents on the metallotropic shift versus turnover of the intermediate alkylidenes, probes **11a–c** and **15a–c** were examined (Scheme 2). The formation of stable complex **12** from **11a** ($R = H$) in the presence of a stoichiometric amount of **4b** indicates that the metallotropic shift could not be initiated from **12** once it is formed. On the other hand, rapid formation of metathesis products **13** ($R = Me$) and **14** ($R = CH_2OPMB$) from similar substrates **11b** ($R = Me$) and **11c** under catalytic conditions implies an efficient initiation of metallotropic shift followed by its termination by the tethered alkene. In comparison, **15a–c**, despite an effective initiation of metallotropic shift, their termination behaviors are markedly different. Substrate **15a** afforded only **16**, which is consistent with the termination mode of silylated alkyne **7c** producing only **8c**.¹² On the other hand, **15b** a *tert*-butyl surrogate of **7d**, afforded both **17a** (30%) and **17b** (41%). The exclusive formation of **18** from **15c**, where a methylene unit of the tether in **15b** is replaced by an oxygen atom, further demonstrates that even a subtle difference in steric and electronic factors of substituents profoundly affects the metallotropic shift and turnover behavior of the equilibrating alkylidenes.

Next, chelation-induced trapping of equilibrating alkylidenes was explored with diyne **19** (Scheme 3). We predicted that the initial relay metathesis-based catalyst delivery^{5a,13} to the trisubstituted double bond from **20** would generate alkylidenes **21–23**. Once the metal center is proximal to the isopropoxide moiety, the chelate formation^{2,10} would ensue, which will shift the equilibrium toward **24**. However, a stoichiometric reaction between **19** and **4b** provided **26** as a sole product without the formation of **24** or **25**. Probably, the unavoidable interaction between one of the mesityl groups and the diyne moiety on **24** is energetically too unfavorable, rendering the rapidly equilibrating alkylidenes **21–23** to be trapped at

electronically most favorable or sterically least hindered site to deliver **26** selectively. On the other hand, the reaction between **19** and a stoichiometric amount of first-generation catalyst **4a** gave a new complex **27** quantitatively. We inferred that contrary to **24** complex **27** can avoid the severe steric clash by positioning the diyne moiety between the two cyclohexyl group of tricyclohexylphosphine ligand, which is unambiguously shown by the X-ray structure.

Although stable enough to be isolated, some alkynyl Ru-alkylidenes retain metathesis activity. With a catalytic amount of **10b** (5 mol %), diyne **9** gave metathesis product **28** in 46% yield. Also, in the presence of added alkene, substrate **9** and **7e** gave RCM-CM product **29** and **30** in 62% and 50% yield, respectively. However, complex **27** did not show metathesis activity under the same conditions.

In conclusion, we have demonstrated that substituent on alkynyl Ru-alkylidenes can effectively modulate their reactivity and metallotropic [1,3]-shift behavior. For the first time, we have obtained X-ray crystal structures of alkynyl Ru-alkylidenes and the reactivity of these complexes was briefly examined. The behaviors of these unprecedented ruthenium complexes provide further insights into the reactivity of Grubbs-type complexes. Studies on the higher homologs of alkynyl Ru-alkylidenes and their metallotropic shift behavior will be reported in due course.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Scheme 1.
Regioselective Trapping of Alkynyl Ru-Alkylidenes

Scheme 2.
 Reactivity Difference of Alkynyl Ru-Alkylidenes

Scheme 3.
Formation of a Chelated Alkynyl Ru-Alkylidene

Scheme 4.
Reactivity of Isolated Alkynyl Ru-Alkylidene **10b**