doi:10.1246/cl.2010.78

Highlight Review

The Diversified Reactivities of 1,5-Bisallenes

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(Received October 16, 2009; CL-098012)

Abstract

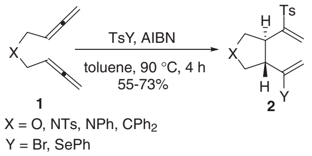
1,5-Bisallenes may undergo radical, carbometallation, cyclometallation, cyclization, and consecutive cascade reactions to form many different 5–7-membered rings, showing diversified reactivities. There is no doubt that the chemistry of 1,5-bisallenes would be enriched by further study.

◆ Introduction

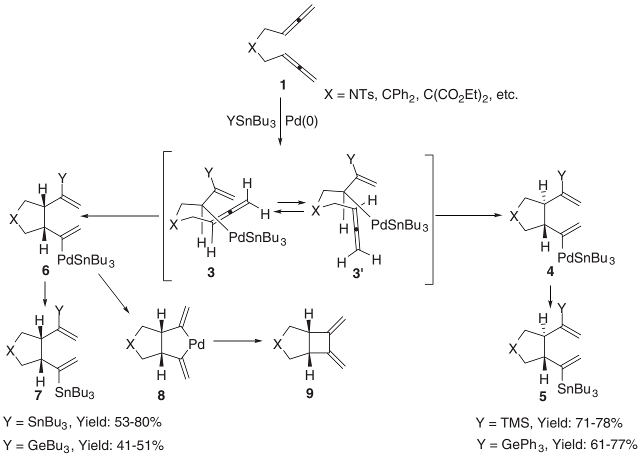
Although the first synthetic allene can be dated back to 1887,[1] the chemistry and synthetic routes of allenes have not been well established because of the wrong notion that these compounds would be highly unstable. In fact, allenes have been found in many natural products with biological activities.[2] According to our own experience, many allenes may even be distilled without any problem. In last decade, they have been demonstrated to show nice reactivities with high selectivities: allenes can be transformed to many useful compounds by controlling reaction conditions, which shows the unique value in organic synthesis.[3,4] Along with the development of allene chemistry, bisallenes, a special class of allenes, have recently attracted interest from organic chemists. Several groups have reported the reactions of 1,5-bisallenes extensively showing their intriguing diversity of reactivities. This highlight summarizes the advances of the chemistry of 1,5-bisallenes.

◆ Radical Cyclization

Kang first reported the radical cyclization of 1,5-bisallenes **1** with TsBr and TsSePh affording *trans*-cyclopentane compounds **2** in 2001 (Scheme 1).[5] However, a mixture of *cis*- and *trans*-cyclopentane products was formed in 22% total yield when TsI was applied with NTs tethered bisallene **1**.



Scheme 1. Radical cyclization.



Scheme 2. Pd-catalyzed cyclization of 1,5-bisallenes with $YSnBu_3$.

◆ Pd-catalyzed Cyclization

Besides the radical reactions above, the Kang group also developed the Pd-catalyzed cyclization of 1,5-bisallenes **1** with silylstannanes or distannanes in 2000 (Scheme 2).[6a] When 1,5-bisallenes **1** were treated with (trimethylsilyl)tributylstannane, *trans* products **5** was formed in the presence of 5 mol % $Pd(PPh_3)_4$ in refluxing THF for 3 h (conditions A) or 5 mol % $(allyl)_2PdCl_2$ in THF at room temperature for 3 h (conditions B). However, *cis* products **7** were afforded with distannane $Bu_3SnSnBu_3$ under the same reaction conditions. Furthermore, if the reaction time was prolonged to 12 h, intramolecular coupling occurred to **6** to generate bicyclo[3.2.0] products **9** via the intermediacy of **8** in 48–62% yields. Similarly, the Pd-catalyzed cyclization of 1,5-bisallenes with germylstannane under similar reaction conditions was reported by Yu, Kang, et al. (Scheme 2).[6b] When the Y group was Bu_3Ge, *cis* products **7** were afforded in 41–51% yields, while with Y being the Ph_3Ge group, *trans* products **5** were formed in 61–77% yields. However, it should be noted that by-product *cis*-fused bicyclic dienes **9** were formed in 14–27% yields in all the reactions except when the tether atom is oxygen. The selectivity of *cis* and *trans* products is considered to be controlled by the steric effect of Y and allene moiety in intermediate **3** or **3′**. When Y is a bulky group such as TMS or $GePh_3$, *trans* products are formed.

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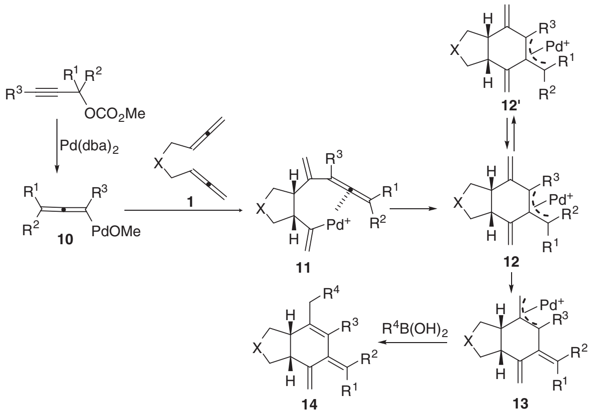
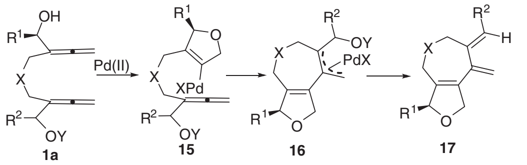


Yield: 41-77%

if R^1 ≠ R^2, R^1 > R^2

Scheme 3. Pd(dba)$_2$-catalyzed three-component cascade cyclization reaction.



X = CH$_2$, NTs, O, SO$_2$
Y = H, Ac
R^1, R^2 = Alkyl, Aryl

Yield: 51-81%

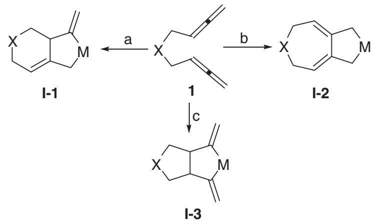
Scheme 4. Pd(II)-catalyzed cyclization of bisallenols.

Recently, this group has developed a three-component cascade cyclization reaction of 1,5-bisallenes with propargylic carbonates and organoboronic acids (Scheme 3).[7] In this reaction, 1,2-allenyl palladium species **10** was generated by oxidative addition of Pd(0) with propargylic carbonates. Subsequently, the intermediate **10** underwent double carbopalladation with 1,5-bisallenes **1** to form *cis* intermediate **11** by the coordination of the Pd with the remaining allene moiety, which was followed by another cyclic carbopalladation with the allene moiety to form intermediate **12**. Due to the presence of the "upper" exo C=C bond, the intermediate **12** would further isomerize to π-allylic intermediate **13**. The stereoselectivity may be explained by the fact that intermediate **12** is more favored in the equilibrium between **12** and **12′** because of the steric repulsion between the Pd center and R^1 group (R^1 > R^2). The final product *cis*-fused bicyclo[4.3.0]nonene **14** was formed by the Suzuki coupling of **13** with organoboronic acids.

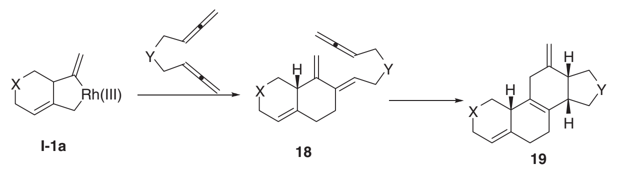
The synthesis of 2,5-dihydrofuran-fused bicyclic products via Pd(II)-catalyzed cyclization of bisallenols has also been developed in this group (Scheme 4).[8] The intramolecular oxypalladation of the 2,3-allenol moiety in bisallenes **1a** with Pd(II) would form 2,5-dihydrofuranyl palladium intermediate **15**, which then underwent intramolecular carbopalladation of another allene moiety in bisallenes **1a** to generate the allyl palladium intermediate **16**. Finally, *trans*-β-hydroxide or acetate elimination would afford product **17** with the R^2 group pointing away from the methylidene group due to steric effects.

◆ Rh-catalyzed Cyclization

Different from the Pd-catalyzed reactions, Rh catalysts usually undergo cyclometallation. Due to the presence of four C=C bonds in one molecule of 1,5-bisallene, there are three different types of cyclometallations (Scheme 5): a) metal coordinative cyclization with an internal C=C bond and a terminal C=C bond to form intermediate **I-1**, b) metal coordinative cyclization with two terminal C=C bonds to form intermediate **I-2**, and c) metal coordinative cyclization with two internal C=C bonds to form intermediate **I-3**.



Scheme 5. Three different types of cyclometallations.



X, Y = C(CO$_2$Me)$_2$, C(CN)$_2$, C(SO$_2$Ph)$_2$, NTs, C(CN)(CO$_2$Et)
Y = X, or Y ≠ X

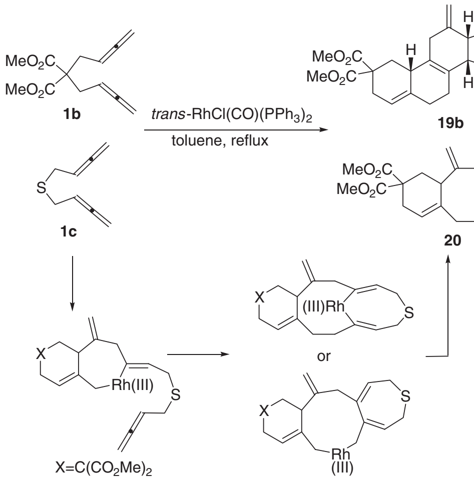
Yield: 57-74%

Scheme 6. RhCl(CO)(PPh$_3$)$_2$-catalyzed reaction of two molecules of 1,5-bisallenes.

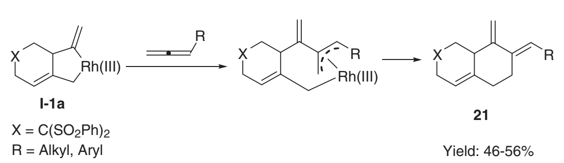
This group has demonstrated that 1,5-bisallenes **1** can form the intermediate **I-1a** with the catalyst *trans*-RhCl(CO)(PPh$_3$)$_2$ in toluene, which may then undergo carbometallation with a second molecule of bisallene, reductive elimination, and intramolecular Diels–Alder reaction to form 18,19-norsteroid derivative **19** in moderate to good yields with excellent diastereoselectivity (Scheme 6).[9a] Using this method, different heterosteroid scaffolds can be easily prepared by the cross-cyclization reaction between two different bisallenes.[9b] It should be noted that when bisallenes **1b** and **1c** were applied to the cross-cyclization, besides the normal product **19b**, tricyclic product **20** was also formed which supported the mechanism starting from the formation of the six-membered ring (Scheme 7).[9b]

Furthermore, bicyclo[4.4.0]decene derivatives **21** were afforded in moderate yields when the intermediate **I-1a** (Scheme 8) was trapped with a monoallene.[9c] The R group is also pointing away from the methylidene group in the final product **21** due to the steric effect.

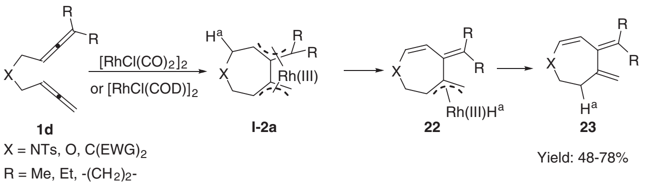
In the presence of catalyst [RhCl(CO)$_2$]$_2$ or [RhCl(COD)]$_2$ in MeCN or DMF, terminal disubstituted 1,5-bisallenes **1d** may form intermediate **I-2a** with a seven-membered ring through **b-type** cyclometallation (Scheme 9).[10] Then the intermediate **I-2a** undergoes β-H^a elimination to form intermediate **22**. Subsequent reductive elimination affords **23** with the regeneration of the rhodium catalyst. There may be other mechanistic pathways involving oxidative addition of the Rh with allenylic C–H bond and cyclic carborhodation to form the intermediate **22**.[11]



Scheme 7. Evidence for the mechanism.



Scheme 8. $RhCl(CO)(PPh_3)_2$-catalyzed reaction of a 1,5-bisallene in the presence of a monoallene.



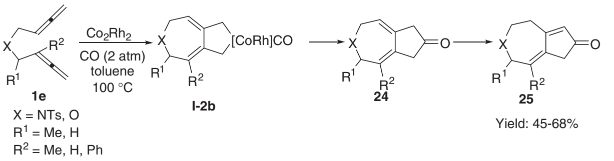
Scheme 9. Rh-catalyzed reaction of terminal disubstituted 1,5-bisallenes-formation of 7-membered ring.

♦ [2 + 2 + 1] Cyclization

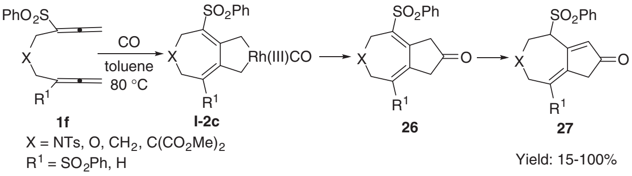
Chung and co-workers reported that Co/Rh nanoparticles catalyzed intramolecular [2 + 2 + 1] cycloadditions of 1,5-bisallenes **1e** (Scheme 10).[12] Carbonylation of intermediate **I-2b** produces **24** which undergo a 1,3-hydrogen shift to form the product **25**. However, terminal disubstituted 1,5-bisallenes **1d** (X = NTs, R = Me) failed to afford the corresponding Pauson–Khand product, a monocyclic seven-membered triene **23** described in Scheme 9 was formed in 75% yield instead.

Very recently, Mukai et al. reported that $[RhCl(CO)dppp]_2$ or $[RhCl(CO)_2]_2$ catalyzed [2 + 2 + 1] cycloadditions of bis(phenylsulfonylallene) derivatives **1f** to form bicyclo[5.3.0]-decadienones **27** (Scheme 11).[13] $[RhCl(CO)dppp]_2$ is better than $[RhCl(CO)_2]_2$ in this reaction, except for the special case when the tether atom X is $C(CO_2Me)_2$. Without the phenylsulfonyl group, no [2 + 2 + 1] product was afforded. When R^1 = H, the yield and selectivity are poor.

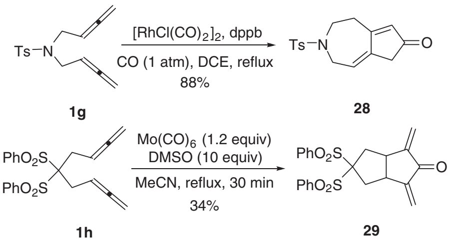
On the other hand, [2 + 2 + 1] Pauson–Khand reactions have also been observed in this group (Scheme 12).[14] Using different metal catalysts Rh and Mo, **1g** and **1h** gave the different Pauson–Khand products **28** and **29** via different intermediates **I-2** and **I-3**. However, the scope of the reaction was very limited.



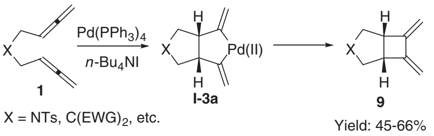
Scheme 10. Co/Rh-catalyzed [2 + 2 + 1] cycloaddition.



Scheme 11. Rh-catalyzed [2 + 2 + 1] cycloaddition.



Scheme 12. Rh- or Mo-catalyzed [2 + 2 + 1] cycloaddition.



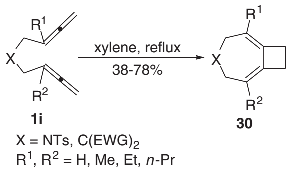
Scheme 13. $Pd(PPh_3)_4$-catalyzed [2 + 2] cycloaddition.

♦ [2 + 2] Cyclization

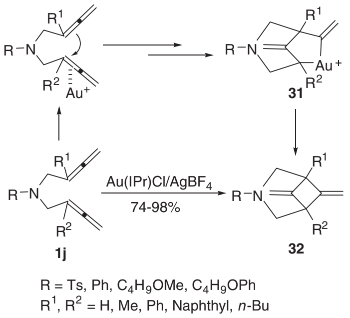
As we all know, the [2 + 2] or [4 + 2] cyclizations of 1,2-bisallenes,[15] 1,4-bisallenes,[16] and 1,6-bisallenes[17] have already been well explored. The [2 + 2] cycloaddition of 1,5-bisallenes show diversified patterns. Using $Pd(PPh_3)_4$ as catalyst, this group observed that 1,5-bisallenes **1** formed the head-to-head bicyclo[3.2.0] products **9** through cyclometallation intermediate **I-3a** and reductive elimination (Scheme 13).[18] The I^- ion plays an important part in the reaction as a ligand to promote reductive elimination of Pd from intermediate **I-3a**.

However, interestingly the thermal [2 + 2] cyclization of 1,5-bisallenes **1i** afforded bicyclo[5.2.0] products **30** via tail-to-tail [2 + 2] cyclization in refluxing xylene (Scheme 14).[18]

Very recently, Kang and Chung reported a very unique Au-catalyzed [2 + 2] cycloaddition of amino-tethered 1,5-bisallenes (Scheme 15).[19] One allene acts as a nucleophilic reagent attacking another Au^+-coordinated allene in 1,5-bisallenes **1j** to form one C–C single bond. The intermediate **31** was recognized as the key intermediate through DFT calculations, which form the final product **32** via reductive elimination.



Scheme 14. Thermal [2 + 2] cycloaddition.



Scheme 15. Au-catalyzed [2 + 2] cycloaddition.

◆ Summary and Outlook

We have summarized in this highlight the recent developments in the area of the reactions of 1,5-bisallenes affording different cyclic structures. Since the early work from Kang's group, various catalytic systems and reactions patterns have been demonstrated during the past decades. The high activity of 1,5-bisallenes lies in the nature of two allenes (four C=C bonds), which may undergo cyclometallation, carbometallation, and consecutive cascade reactions catalyzed by Rh, Pd, Au, etc. Moreover, the possibility of constructing complicated structural units from the reactions of 1,5-bisallenes makes this type of allene synthetically attractive. There is no doubt that the chemistry of 1,5-bisallenes would be further explored, which would emphasize 1) expansion of substrates scope especially substituent effect, 2) extensive search of metal catalysts including chiral catalysts, 3) introduction of other nucleophilic or electrophilic reagents, and 4) mechanism and new reaction pathways.

Financial support from the Major State Basic Research and Development Program (No. 2006CB806105) and National Natural Science Foundation of China (No. 20732005) for our research in this area is appreciated.

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