

# Cationic Rhodium(I) Complex-Catalyzed Cotrimerization of Propargyl Esters and Arylacetylenes Leading to Substituted Dihydropentalenes

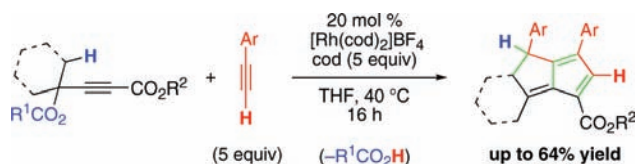
Yu Shibata,<sup>†</sup> Keiichi Noguchi,<sup>‡</sup> and Ken Tanaka<sup>\*,†</sup>

Department of Applied Chemistry, Graduate School of Engineering, and Instrumentation Analysis Center, Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan

tanaka-k@cc.tuat.ac.jp

Received October 19, 2010

## ABSTRACT



It has been established that a cationic rhodium(I)/cod complex catalyzes the cotrimerization of propargyl esters and arylacetylenes, leading to substituted dihydropentalenes, in the presence of excess cod through elimination of carboxylic acids.

Transition-metal carbenoids are known to be valuable key intermediates for various synthetic transformations, such as cycloaddition reactions, olefin metathesis, reactions via reactive ylides, and insertion reactions into  $\sigma$  bonds.<sup>1</sup> To avoid the use of hazardous diazo compounds as metal carbenoid precursors, facile methods for generation of transition-metal carbenoids from alkynes have been developed.<sup>2–8</sup> In most cases, *intramolecular* attack of a nucleophile on the alkyne carbon through transition-metal-catalyzed activation of the alkyne triple bond affords a (vinyl)metal

species that is subsequently transformed into a metal carbenoid.<sup>3</sup> Although a large number of such *intramolecular* reactions have been reported,<sup>3</sup> *intermolecular* variants using external nucleophiles have been reported in a limited number.<sup>4–7</sup> For example, Iwasawa, Kusama, and co-workers reported the platinum(II)-catalyzed cycloaddition of allenes

(3) For recent reviews of catalyses via metal carbenoids generated from  $\beta$ -akynylcarbonyl compounds and propargyl esters, see: (a) Ohe, K.; Miki, K. *J. Synth. Org. Chem. Jpn.* **2009**, *67*, 1161. (b) Marion, N.; Nolan, S. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 2750. (c) Gorin, D. J.; Toste, F. D. *Nature* **2007**, *446*, 395. (d) Kusama, H.; Iwasawa, N. *Chem. Lett.* **2006**, *35*, 1082. (e) Miki, K.; Uemura, S.; Ohe, K. *Chem. Lett.* **2005**, *34*, 1068.

(4) Kusama, H.; Ebisawa, M.; Funami, H.; Iwasawa, N. *J. Am. Chem. Soc.* **2009**, *131*, 16352.

(5) (a) Ye, L.; Cui, L.; Zhang, G.; Zhang, L. *J. Am. Chem. Soc.* **2010**, *132*, 3258. (b) Ye, L.; He, W.; Zhang, L. *J. Am. Chem. Soc.* **2010**, *132*, 8550. (c) Lu, B.; Li, C.; Zhang, L. *J. Am. Chem. Soc.* **2010**, *132*, 14070.

(6) Our research group reported the cationic rhodium(I) complex-catalyzed asymmetric cotrimerization of acetylenedicarboxylates and alkenes via cationic rhodium(I) carbenoids generated through ring contraction of rhodacyclopentenes. See: Shibata, Y.; Noguchi, K.; Hirano, M.; Tanaka, K. *Org. Lett.* **2008**, *10*, 2825.

(7) The palladium(II)-catalyzed cotrimerization of diarylacetylenes, leading to dihydrocyclopenta[*a*]indenes, via palladium(II) carbenoids generated through ring contraction of palladacycloheptatrienes was reported. See: Wu, Y.-T.; Kuo, M.-Y.; Chang, Y.-T.; Shin, C.-C.; Wu, T.-C.; Tai, C.-C.; Cheng, T.-H.; Liu, W.-S. *Angew. Chem., Int. Ed.* **2008**, *47*, 9891.

<sup>†</sup> Department of Applied Chemistry.

<sup>‡</sup> Instrumentation Analysis Center.

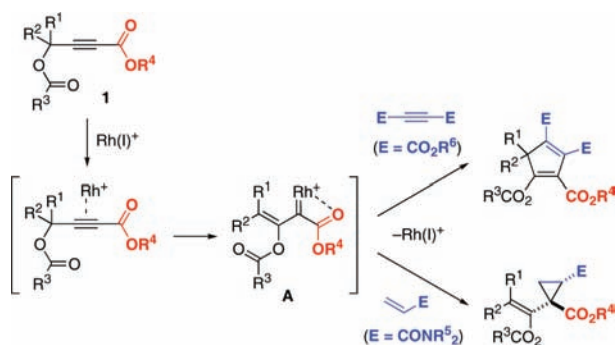
(1) For recent reviews, see: (a) Herndon, J. W. *Coord. Chem. Rev.* **2009**, *253*, 1517. (b) Wu, Y.-T.; Kurahashi, T.; De Meijere, A. *J. Organomet. Chem.* **2005**, *690*, 5900. (c) Dötz, K. H.; Koch, A.; Werner, M. In *Handbook of Functionalized Organometallics*; Knochel, P., Ed.; Wiley-VCH: Weinheim, 2005; p 451. (d) *Metal Carbenes in Organic Synthesis*; Dötz, K. H., Ed.; Topics in Organometallic Chemistry; Springer-Verlag: Berlin, 2004; Vol. 13. (e) Zaragoza Dörwald, F. *Metal Carbenes in Organic Synthesis*; Wiley-VCH: Weinheim, 1998. (f) Doyle, M. P.; McKervey, M. A.; Ye, T. *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds: From Cyclopropanes to Ylides*; Wiley-Interscience: New York, 1998.

(2) For recent reviews of catalyses via metal carbenoids generated from  $\alpha,\omega$ -enynes, see: (a) Lee, S. I.; Chatani, N. *Chem. Commun.* **2009**, 371. (b) Jiménez-Núñez, E.; Echavarren, A. M. *Chem. Rev.* **2008**, *108*, 3326. (c) Zhang, L.; Sun, J.; Kozmin, S. A. *Adv. Synth. Catal.* **2006**, *348*, 2271.

with alkenyl ethers via generation of platinum(II) carbenoids through *intermolecular* nucleophilic attack of alkenyl ethers on allenes.<sup>4</sup> Recently, Zhang and co-workers reported the gold(I)-catalyzed oxidative cyclization via generation of gold(I) carbenoids through *intermolecular* nucleophilic attack of pyridine *N*-oxides on alkynes.<sup>5</sup> In this paper, we describe the cationic rhodium(I)/cod complex-catalyzed cotrimerization of propargyl esters and arylacetylenes, leading to substituted dihydropentalenes,<sup>9</sup> presumably via generation of a cationic rhodium(I) carbenoid<sup>10,11</sup> through *intermolecular* attack of a rhodium arylacetylide on the propargyl ester followed by the reaction of another arylacetylene and elimination of a carboxylic acid.

Our research group has recently reported the cationic rhodium(I) complex-catalyzed [3 + 2] and [2 + 1] cycloadditions of alkoxy carbonyl-substituted propargyl esters **1** with electron-deficient alkynes and alkenes presumably via generation of carbonyl-stabilized cationic rhodium(I) vinylcarbenoids **A** through the *intramolecular* 1,2-acyloxy rearrangement (Scheme 1).<sup>8</sup>

Scheme 1

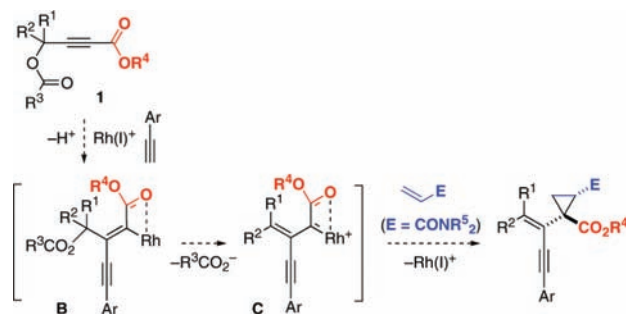


On the other hand, it is well-known that the cationic rhodium(I) complex is able to catalyze the cross-dimerization reactions between terminal alkynes and internal alkynes.<sup>12</sup> In these reactions, the cationic rhodium(I) complex first reacts with the terminal alkyne to generate the corresponding rhodium acetylide, which subsequently reacts with the internal alkyne to generate a (vinyl)rhodium intermediate.<sup>12</sup> Thus we designed a new method for the generation of the cationic rhodium(I) carbenoids as shown in Scheme 2. *Intermolecular* nucleophilic attack of the rhodium arylacetylide on alkoxy carbonyl-substituted propargyl ester **1** would

(8) (a) Shibata, Y.; Noguchi, K.; Tanaka, K. *J. Am. Chem. Soc.* **2010**, *132*, 7896. For examples of catalyses via metal carbenoids through the intramolecular 1,2-acyloxy rearrangement of propargyl esters, see: (b) Rautenstrauch, V. *Tetrahedron Lett.* **1984**, *25*, 3845. (c) Rautenstrauch, V. *J. Org. Chem.* **1984**, *49*, 950. (d) Mainetti, E.; Mouriès, V.; Fensterbank, L.; Malacria, M.; Marco-Contelles, J. *Angew. Chem., Int. Ed.* **2002**, *41*, 2132. (e) Miki, K.; Ohe, K.; Uemura, S. *Tetrahedron Lett.* **2003**, *44*, 2019. (f) Miki, K.; Ohe, K.; Uemura, S. *J. Org. Chem.* **2003**, *68*, 8505. (g) Johansson, M. J.; Gorin, D. J.; Staben, S. T.; Toste, F. D. *J. Am. Chem. Soc.* **2005**, *127*, 18002.

(9) Recent examples of the efficient synthesis of substituted dihydropentalenes, see: (a) Gotoh, H.; Ogino, H.; Ishikawa, H.; Hayashi, Y. *Tetrahedron* **2010**, *66*, 4894. (b) Hong, B.-C.; Shr, Y.-J.; Wu, J.-L.; Gupta, A. K.; Lin, K.-J. *Org. Lett.* **2002**, *4*, 2249. (c) Ref 7.

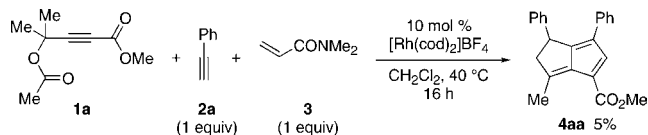
Scheme 2



generate (vinyl)rhodium intermediate **B**. Subsequent elimination of a carboxylic acid would generate carbonyl-stabilized cationic rhodium(I) vinylcarbenoid **C**, which reacts with an acrylamide derivative to give a trisubstituted cyclopropane.

We first examined the reaction of methoxycarbonyl-substituted propargyl ester **1a**, phenylacetylene (**2a**), and *N,N*-dimethylacrylamide (**3**) at 40 °C in  $\text{CH}_2\text{Cl}_2$  in the presence of 10 mol % of  $[\text{Rh}(\text{cod})_2]\text{BF}_4$ , which was effective for the reaction shown in Scheme 1. However, an unexpected cotrimerization product between **1a** and **2a**, dihydropentalene **4aa**, was obtained in low yield instead of the expected cyclopropanation product (Scheme 3).

Scheme 3

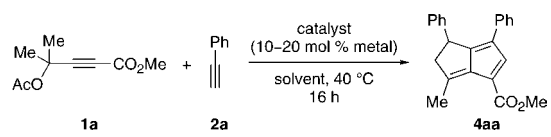


We then focused our attention on the synthesis of dihydropentalene **4aa** and examined the reaction conditions in the absence of acrylamide **3** to improve the yield of **4aa** (Table 1). However, the reaction of **1a** and **2a** in the absence of **3** did not furnish **4aa** at all (entry 1). It was anticipated that coordination of **3** to the cationic rhodium plays an

(10) For examples of catalyses via rhodium(I) carbenoids, see: (a) Nishimura, T.; Maeda, Y.; Hayashi, T. *Angew. Chem., Int. Ed.* **2010**, *49*, 7324. (b) Ref.8a (c) Ref 6. (d) Barluenga, J.; Vicente, R.; López, L. A.; Tomás, M. *J. Am. Chem. Soc.* **2006**, *128*, 7050. (e) Barluenga, J.; Vicente, R.; López, L. A.; Tomás, M. *J. Organomet. Chem.* **2006**, *691*, 5642. (f) Barluenga, J.; Vicente, R.; López, L. A.; Tomás, M. *Tetrahedron* **2005**, *61*, 11327. (g) Barluenga, J.; Vicente, R.; López, L. A.; Rubio, E.; Tomás, M.; Álvarez-Rúa, C. *J. Am. Chem. Soc.* **2004**, *126*, 470.

(11) For reviews of catalyses via rhodium(II) carbenoids, see: (a) Davies, H. M. L.; Walji, A. M. In *Modern Rhodium-Catalyzed Organic Reactions*; Evans, P. A., Tsuji, J., Eds.; Wiley-VCH: Weinheim, Germany, 2005; p 301. (b) Doyle, M. P. In *Modern Rhodium-Catalyzed Organic Reactions*; Evans, P. A., Tsuji, J., Eds.; Wiley-VCH: Weinheim, Germany, 2005; p 341.

(12) For selected recent examples, see: (a) Matsuyama, N.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem.* **2009**, *74*, 3576. (b) Ito, J.; Kitase, M.; Nishiyama, H. *Organometallics* **2007**, *26*, 6412. (c) Nishimura, T.; Guo, X.-X.; Ohnishi, K.; Hayashi, T. *Adv. Synth. Catal.* **2007**, *349*, 2669. (d) Katagiri, T.; Tsurugi, H.; Funayama, A.; Satoh, T.; Miura, M. *Chem. Lett.* **2007**, *36*, 830.

**Table 1.** Optimization of Reaction Conditions<sup>a</sup>


entry	catalyst	catalyst (mol %)	additive	solvent	2a (equiv)	yield (%) <sup>a</sup>
1	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	CH <sub>2</sub> Cl <sub>2</sub>	2	0
2	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	toluene	2	<5
3	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	Et <sub>2</sub> O	2	5
4	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	DME	2	15
5	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	dioxane	2	14
6	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	THF	2	20
7	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	acetone	2	7
8	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	-	CH <sub>3</sub> CN	2	<5
9	[Rh(nbd) <sub>2</sub> ]BF <sub>4</sub>	10	-	THF	2	<5
10	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub> /BINAP	10	-	THF	2	5
11	[Rh(cod) <sub>2</sub> ]SbF <sub>6</sub>	10	-	THF	2	<5
12	[RhOAc(cod)] <sub>2</sub>	10	-	THF	2	0
13	[RhCl(cod)] <sub>2</sub>	10	-	THF	2	0
14	[RhCl(cod)] <sub>2</sub> /2AgBF <sub>4</sub>	10	-	THF	2	11
15	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	cod (5 equiv)	THF	2	30
16	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	cod (5 equiv)	THF	5	33
17	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	10	cod (5 equiv)	THF	2	38
18	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	20	cod (5 equiv)	THF	5	59 <sup>b</sup>
19 <sup>c</sup>	[Rh(cod) <sub>2</sub> ]BF <sub>4</sub>	20	cod (5 equiv)	THF	5	42 <sup>b</sup>
20	[IrCl(cod)] <sub>2</sub> /2AgBF <sub>4</sub>	20	cod (5 equiv)	THF	5	0

<sup>a</sup> NMR yield. <sup>b</sup> Isolated yield. <sup>c</sup> At 25 °C.

important role to promote the formation of **4aa**. Thus, the effect of solvents, possessing diverse coordination ability, on the present catalysis was investigated (entries 2–8), which revealed that moderately coordinative solvents were effective (entries 3–7) and the use of THF furnished **4aa** in the highest yield (entry 6). The effect of ligands and counteranions of the rhodium catalysts was also examined (entries 9–14). The use of nbd (norbornadiene) or BINAP as a ligand significantly lowered the product yield (entries 9 and 10). The use of SbF<sub>6</sub> as a counteranion also significantly lowered the product yield (entry 11), and neutral rhodium(I) complexes failed to catalyze this reaction (entries 12 and 13). In situ generation of the cationic rhodium(I)/monocod complex, [Rh(cod)]BF<sub>4</sub>, by mixing [Rh(cod)Cl]<sub>2</sub> and AgBF<sub>4</sub> resulted in low yield (entry 14). On the contrary, the addition of excess cod increased the yield of **4aa** to 30% (entry 15). In this reaction, oligomerization of **2a** proceeded as a major side reaction. Therefore, increasing the amount of **2a** to 5 equiv was attempted, while only a slight increase of the yield was observed (entry 16). Fortunately, the use of excess **2a** was effective when the catalyst loading was increased to 20 mol %, and the yield of **4aa** was improved to 59% (entries 17 vs 18). Under these optimized reaction conditions, the reaction proceeded even at room temperature to give **4aa** in 42% yield (entry 19). Finally, we have determined that the present dihydropentalene formation could not be catalyzed by a cationic iridium(I)/cod complex (entry 20).

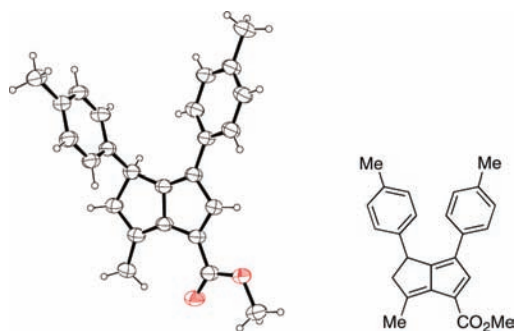
Next, the scope of this reaction was examined as shown in Table 2. With respect to terminal alkynes, not only

**Table 2.** Rhodium-Catalyzed Cotrimerization of Propargyl Esters **1a–f** and Terminal Alkynes **2a–f**<sup>a</sup>

entry	1	2	4 / isolated yield
1			<b>4aa</b> / 59%
2			<b>4ab</b> / 47%
3			<b>4ac</b> / 41%
4			<b>4ad</b> / 50%
5			<b>4ae</b> / 38%
6			<b>4af</b> / 0%
7			<b>4ba</b> / 63%
8			<b>4ca</b> / 64%
9			<b>4aa</b> / 32%
10			<b>4aa</b> / <5%
11			<b>4fa</b> / 33% <sup>b</sup>

<sup>a</sup> Reactions were conducted using [Rh(cod)<sub>2</sub>]BF<sub>4</sub> (20 mol %), cod (5 equiv), **1a–f** (1 equiv), and **2a–f** (5 equiv) in THF at 40 °C for 16 h. <sup>b</sup> An unidentified dihydropentalene isomer was generated in ca. 7% yield, although it was not isolated in a pure form.

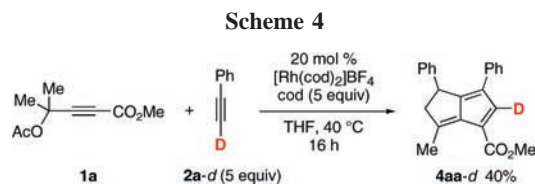
phenylacetylene (**2a**, entry 1) but also various arylacetylenes **2b–e** (entries 2–5) reacted with **1a** to give the corresponding dihydropentalenes in moderate yields. The structure of **4ab** was unambiguously confirmed by X-ray crystallographic analysis (Figure 1). However, alkylacetylene **2f**, possessing the less acidic sp C–H bond, failed to react with **1a** (entry



**Figure 1.** ORTEP drawing of **4ab** with ellipsoids at 30% probability.

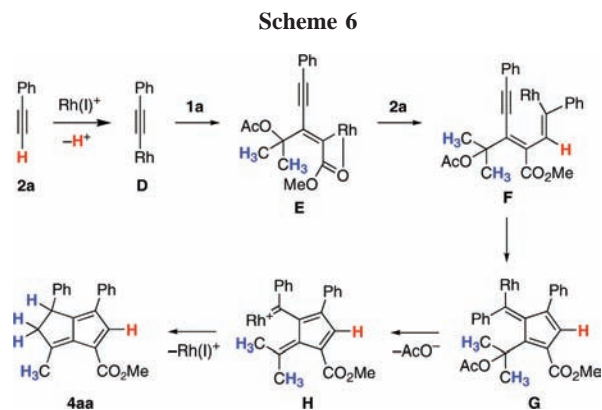
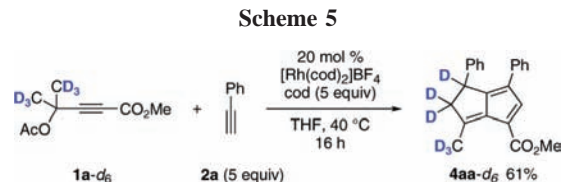
6). With respect to propargyl esters, not only methyl ester **1a** but also ethyl and isopropyl esters **1b,c** reacted with **2a** to give the corresponding dihydropentalenes in good yields (entries 7 and 8). As a leaving group, the benzyloxy group could be employed instead of the acetoxy group, although the yield of **4aa** decreased (entry 9). However, the methoxy group was ineffective (entry 10). Cyclohexane derivative **1f** could also participate in this reaction to give tricyclic dihydropentalene **4fa** (entry 11).

To elucidate a reaction mechanism, deuterium labeling experiments were conducted. The reaction of **1a** and **2a-d**, possessing deuterium at the alkyne terminus, led to selective incorporation of deuterium at the vinylic position of product **4aa-d** (Scheme 4). The reaction of **1a-d<sub>6</sub>**, derived from



deuterated acetone [(CD<sub>3</sub>)<sub>2</sub>CO], and **2a** led to selective incorporation of one deuterium at the benzylic position of product **4aa-d<sub>6</sub>** (Scheme 5).

On the basis of these observations, the formation of **4aa** from **1a** and **2a** might proceed through the mechanism shown in Scheme 6. Carborhodation of **1a** with rhodium phenylacetylide **D** furnishes (vinyl)rhodium intermediate **E**, which reacts with another **2a** to generate (dienyl)rhodium intermediate **F**. Subsequent intramolecular carborhodation to the



alkyne triple bond affords intermediate **G**. Elimination of acetic acid generates carbonyl-stabilized cationic rhodium(I) carbenoid **H**, which inserts into the C–H bond<sup>13</sup> of the methyl group to give **4aa**.

In conclusion, we have established that a cationic rhodium(I)/cod complex catalyzes the cotrimerization of propargyl esters and arylacetylenes, leading to substituted dihydropentalenes, in the presence of excess cod through elimination of carboxylic acids. Future work will focus on further utilization of the cationic rhodium(I) carbenoids in organic synthesis.

**Acknowledgment.** This work was supported partly by Grants-in-Aid for Scientific Research (Nos. 20675002 and 21•906) from MEXT, Japan. We thank Umicore for generous support in supplying rhodium complexes.

**Supporting Information Available:** Experimental procedures, compound characterization data, and an X-ray crystallographic information file. This material is available free of charge via the Internet at <http://pubs.acs.org>.

OL1025266

(13) For a recent review of catalytic insertion of metal carbenoids into C–H bonds, see: Davies, H. M. L.; Manning, J. R. *Nature* **2008**, *451*, 417.