Synthetic Methods

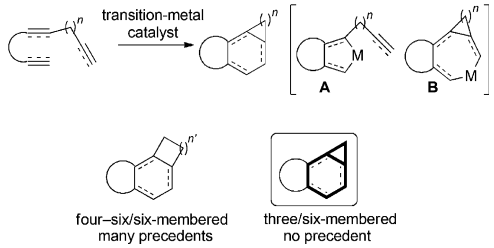
DOI: 10.1002/ange.201409155

Stereospecific and Stereoselective Rhodium(I)-Catalyzed Intramolecular [2+2+2] Cycloaddition of Allene-Ene-Ynes: Construction of Bicyclo[4.1.0]heptenes**

*Yuu Ohta, Shigeo Yasuda, Yuka Yokogawa, Kei Kurokawa, and Chisato Mukai**

Abstract: *Treatment of the allene-ene-yne substrates with [{RhCl(CO)$_2$}$_2$] effected the intramolecular [2+2+2]-type ring-closing reaction to produce various of tri- and tetracyclic derivatives containing a cyclopropane ring. The reaction is highly stereoselective as well as stereospecific with good to excellent yields.*

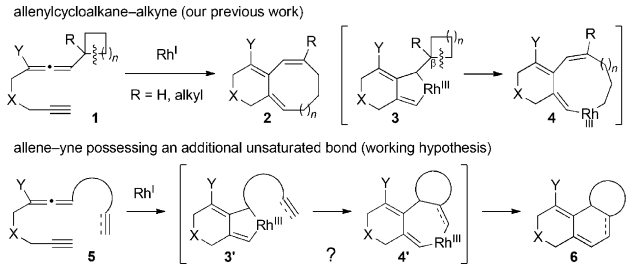
The transition-metal-catalyzed [2+2+2] cycloaddition reactions of unsaturated compounds provide a powerful step- and atom-economical methodology for the construction of various carbo- or heterocyclic six-membered rings.[1] Intramolecular variants straightforwardly enable the chemo- and regioselective construction of complex polycyclic skeletons from simple acyclic compounds. A number of transition-metal-catalyzed intramolecular [2+2+2] cycloadditions of the three C–C π bonds produce tricyclic skeletons (Scheme 1).[1] The



Scheme 1. Transition-metal-catalyzed intramolecular [2+2+2] cycloaddition: construction of various-sized tricyclic skeletons.

reaction is generally thought to proceed by 1) the formation of the metallabicyclic intermediate **A**, 2) the insertion of the remaining π bond into the C–metal bond of **A** to form the intermediate **B**, and 3) reductive elimination of the metal from **B**. There have been many examples regarding the intramolecular [2+2+2] cycloaddition of substrates ($n=3,4$) which affords the tricyclic compounds containing six/six-membered ($n=4$) or five/six-membered ($n=3$) frameworks.[1] The construction of four/six-membered frameworks ($n=2$) based on the intramolecular [2+2+2] cycloaddition have also been recorded by several groups.[1,2] However, there are no precedent available for the direct construction of three/six-membered frameworks ($n=1$) by the intramolecular [2+2+2] cycloaddition.[3] Thus, the direct construction of the highly strained three-membered ring seems to be hard because of the geometric requirement for the insertion step of the remaining π bond into the carbon–metal bond of **A** ($n=1$).[4] In contrast, the bicyclo[4.1.0]heptane ring system (three/six-membered framework) is found as a core structure in various natural products and biologically active compounds.[5]

We recently disclosed that the rhodium(I)-catalyzed intramolecular cycloaddition of the allenylcycloalkane-alkynes **1** ($n=1,2$) efficiently afforded the corresponding bicyclic compounds **2** ($n=1,2$; Scheme 2).[6,7] We presumed



Scheme 2. Rhodium(I)-catalyzed intramolecular cyclization of allene-ynes.

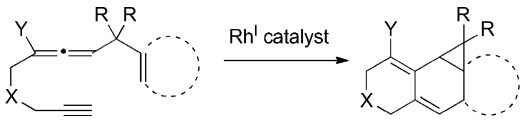
that these reactions would proceed by the initial formation of the rhodabicyclo[4.3.0] intermediate **3**,[6,8] followed by the β-carbon elimination to form the intermediate **4**,[9] which must collapse to the final products through reductive elimination. The plausible key intermediate **3** could accelerate the cleavage of the unfunctionalized C–C bond of cyclobutane ($n=1$) by relief of the high ring-strain energy (26.3 kcal mol^{-1}).[6a,10] This method was applied to the ring-opening of the normal-sized cyclopentane ($n=2$, ring-strain energy: 6.3 kcal mol^{-1}).[6b,10] We envisaged that the allene-alkyne derivatives **5**, possessing an additional π component instead of cycloalkane, would react with the rhodium(I) catalyst,[11] and in analogy to the conversion of **1** into **3**, form the intermediate **3′**. The insertion of the remaining π component to the C–Rh bond of the formed **3′** would produce the tricyclic rhodacycle **4′** if the β-hydride elimination from **3′** could be avoided. The resulting **4′** would then be transformed into the tricyclic product **6**.

[*] Y. Ohta, Dr. S. Yasuda, Y. Yokogawa, K. Kurokawa, Prof. Dr. C. Mukai
Division of Pharmaceutical Sciences, Graduate School of Medical Sciences, Kanazawa University
Kakuma-machi, Kanazawa 920-1192 (Japan)
E-mail: mukai@p.kanazawa-u.ac.jp

[**] We are grateful for the support of this research by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology (Japan).

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201409155.

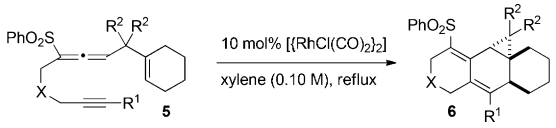
There are two examples dealing with the intramolecular [2+2+2] cycloaddition of allene derivatives. One is the report from Sato and Saito on the ruthenium-catalyzed intramolecular [2+2+2] cycloaddition of allene-ene-ynes,[12] thus resulting in the construction of the fused tricyclic skeletons in a highly stereoselective manner. The other is the rhodium(I)-catalyzed intramolecular [2+2+2] cycloaddition of bis-(allene)-ynes by Solà, Pla-Quintana, and co-workers.[13] We now describe the preliminary results of the rhodium(I)-catalyzed intramolecular [2+2+2] cycloaddition of allene-ene-ynes,[14–17] a reaction allows the preparation of the tri- and tetracyclic derivatives containing bicyclo[4.1.0]heptene skeletons (Scheme 3).



Scheme 3. This study: rhodium(I)-catalyzed intramolecular [2+2+2] cycloaddition of allene-ene-ynes.

Our initial study employed the phenylsulfonylallene-alkyne **5a**, having cyclohexenyl and dimethyl groups at the allenic terminus (Table 1, entry 1), the latter of which was introduced to avoid the unfavorable β-hydride elimination of the possible rhodacycle intermediate (e.g., **3′**; Scheme 2). After careful screening, we found that the use of $[\{RhCl(CO)_2\}_2]$ in refluxing xylene was suitable for our purpose to provide the expected tetracyclic derivative **6a** (72% yield; Table 1, entry 1).[18] The optimized reaction conditions were then applied to several other allene-internal alkyne species **5**. The ethynyl derivative **5b** gave the tetracyclic product **6b** in 89% yield (entry 2).[19] The reaction

Table 1: $[\{RhCl(CO)_2\}_2]$-catalyzed [2+2+2] cycloaddition of allene-ene-ynes **5**.

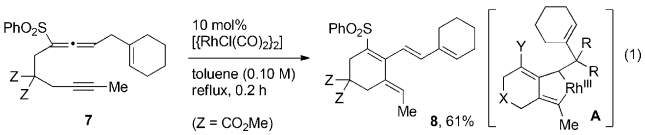


Entry	5	R^1	R^2	X	t [h]	Yield [%][a]
1	**5a**	H	Me	$C(CO_2Me)_2$	0.2	**6a**: 72
2	**5b**	Me	Me	$C(CO_2Me)_2$	0.3	**6b**: 89
3[b,c]	**5c**	*n*Bu	Me	$C(CO_2Me)_2$	1	**6c**: 99
4[b,c]	**5d**	CO_2Me	Me	$C(CO_2Me)_2$	1	**6d**: 99
5	**5e**	TMS	Me	$C(CO_2Me)_2$	0.3	**6e**: 78
6	**5f**	CH_2OH	Me	$C(CO_2Me)_2$	0.3	**6f**: 97
7	**5g**	Me	Me	$C(SO_2Ph)_2$	0.2	**6g**: 97
8[b]	**5h**	*n*Bu	Me	$C(CH_2O)_2CMe_2$	0.1	**6h**: 93
9[b]	**5i**	*n*Bu	Me	$C(CH_2OH)_2$	0.1	**6i**: 99
10	**5j**	*n*Bu	Me	NTs	0.5	**6j**: 77
11	**5k**	*n*Bu	Me	O	0.5	**6k**: 87
12	**5l**	Me	-$(CH_2)_5$- (R^2,R^2)	$C(CO_2Me)_2$	0.5	**6l**: 89

[a] Yield of the isolated product. [b] Toluene was used as solvent. [c] Reaction was performed at 80°C. TMS = trimethylsilyl, Ts = 4-toluenesulfonyl.

of a longer tethered 2-heptynyl analogue (**5c**) smoothly proceeded at a lower temperature (in toluene at 80°C) to afford the cycloadduct **6c** in 99% yield (entry 3). It was shown that the electron-withdrawing group did not interrupt this [2+2+2] cycloaddition. Indeed, the substrate **5d** furnished the cyclized product **6d** in 99% yield (entry 4), and both the TMS (**5e**) and hydroxymethyl (**5f**) groups at the alkyne terminus provided the corresponding cycloadducts **6e** (78% yield) and **6f** (97% yield; entries 5 and 6). The other three substrates **5g**, **5h**, and **5i** with *gem*-disubstitution[20] were exposed to the standard reaction conditions to furnish **6g** in 97% yield (entry 7), **6h** in 93% yield (entry 8), and **6i**[21] in 99% yield (entry 9). The nitrogen (**5j**) and oxygen (**5k**) congeners produced the corresponding aza-compound **6j** (77% yield) and oxa-compound **6k** (87% yield; entries 10 and 11). The substrate **5l** with a cyclohexyl group instead of a dimethyl group at the allenic position was successfully be converted into the pentacyclic adduct **6l** in 89% yield (entry 12).

As predicted on the basis of the mechanistic hypothesis described in Scheme 2, the unsubstituted simple cyclohexenylmethyl substrate **7** did not yield the desired tetracyclic product at all, but the tetraene compound **8** was obtained in 61% yield as a single *E* isomer [Eq. (1)]. This result

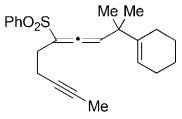
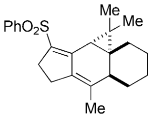
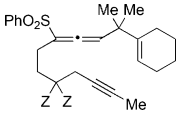
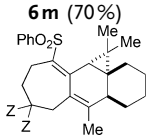
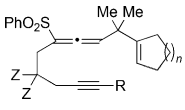
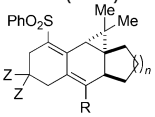


supported our hypothesis which includes the initial formation of **A** (R = H), which would be susceptible to β-hydride elimination,[11a,22] but **A** (R = Me) derived from substrate **5b** no longer has a β-hydrogen atom and undergoes the [2+2+2] ring-closing pathway. Thus, it became clear that the geminal disubstituent moiety at the allenic position of the substrates **5** is essential for this novel [2+2+2] cycloaddition.[23]

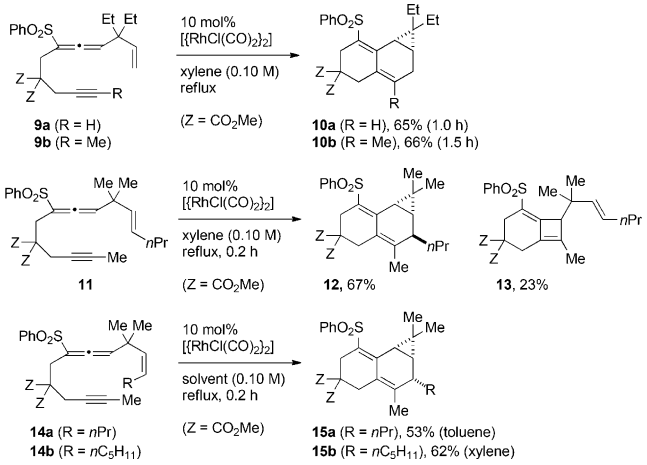
The substrate scope of this newly developed reaction was evaluated (Table 2). Treatment of the one-carbon-shortened substrate **5m** with $[\{RhCl(CO)_2\}_2]$ effected the formation of the five/six-membered framework to produce **6m** in 70% yield (entry 1). In contrast, the larger-sized tetracyclic product **6n**, containing a seven-membered ring, was obtained in 85% yield (entry 2). The substrates possessing a cyclopentenyl (**5o**) or cycloheptenyl (**5p**) ring instead of a cyclohexenyl group as alkene counterparts also underwent the cycloaddition to furnish the corresponding cycloadducts **6o** (80%) and **6p** (99%; entries 3 and 4).

We next examined the reactions of the substrates with acyclic alkenes (Scheme 4). Treatment of the substrates **9a** and **9b**, possessing simple vinyl groups as the alkene component, with $[\{RhCl(CO)_2\}_2]$ afforded the tricyclic compounds **10a** (65% yield) and **10b** (66% yield), respectively. Both the *E*- and *Z*-alkene derivatives were independently subjected to the ring-closing reaction conditions to determine whether the reactions occurred in a stereospecific manner and/or a stereoselective manner. Treatment of the *E*-alkene derivative **11** with $[\{RhCl(CO)_2\}_2]$ under the standard reaction

Table 2: [{RhCl(CO)$_2$}$_2$]-catalyzed [2+2+2] cycloaddition of other allene-ene-yne substrates **5**.[a,b]

Entry	5	t [h]	6 (yield[c])
1	 **5m**	0.2	 **6m** (70%)
2	 **5n**	0.3	 **6n** (85%)
3[d]	 **5o**: $n=1$, R = H	0.3	 **6o**: $n=1$, R = H (80%)
4[e]	**5p**: $n=3$, R = Me	0.5	**6p**: $n=3$, R = Me (99%)

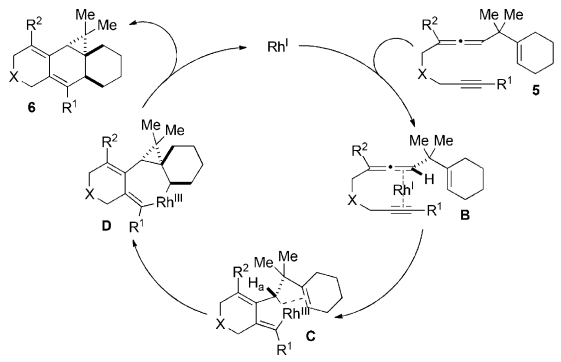
[a] Reaction conditions: 0.10 M solution of allene-ene-yne was treated with 10 mol% of [RhCl(CO)$_2$]$_2$ in refluxing toluene under nitrogen atmosphere. [b] Z = CO_2Me. [c] Yield of the isolated product. [d] Reaction was performed in refluxing xylene. [e] Reaction was performed at 80 °C.



Scheme 4. [{RhCl(CO)$_2$}$_2$}]-catalyzed [2+2+2] cycloaddition of acyclic alkene substrates **9**, **11**, and **14**.

conditions gave the [2+2+2] cycloadduct **12** with *trans* stereochemistry between the *n*-propyl residue and the cyclopropyl ring in 67% yield as a single diastereomer. The cyclobutene derivative **13** (23% yield) was obtained as a by-product. The formation of **13** was tentatively interpreted by the reductive elimination of the rhodium catalyst from the rhodabicyclo-[4.3.0] intermediate **3′** (Scheme 2).[24] In contrast, the (*Z*)-alkene derivative **14a** gave **15a**, which is a *cis*-isomer of **12**, in 53% yield as a single diastereomer.[25] Another *Z*-alkene derivative, **14b**, also afforded the corresponding *cis*-adduct **15b** in 62% yield.[26] Thus, it can be concluded that this intramolecular [2+2+2] cycloaddition is highly stereoselective as well as stereospecific.

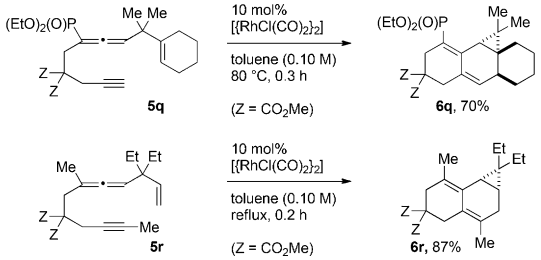
A plausible mechanism for this highly stereoselective and stereospecific [2+2+2] cycloaddition is proposed as shown for



Scheme 5. Plausible mechanism.

the conversion of **5** into **6** (Scheme 5). The initial coordination of **5** with rhodium(I) would occur between an allenic distal double bond and an alkyne to form the intermediate **B**, which should immediately collapse to the bicyclic rhodacyclopentene intermediate **C** by an oxidative ring-closing reaction. The insertion of the tethered alkene into the C(sp^3)–Rh^{III} bond would stereoselectively occur from the opposite face to the C–H$_a$ bond, thus resulting in the intermediate **D**. The reductive elimination of rhodium(III) from **D** would then give the product **6**.[27]

It should be mentioned that a phenylsulfonyl substituent on the allenyl moiety was not mandatory for this transformation (Scheme 6). In fact, upon exposure to the standard



Scheme 6. [{RhCl(CO)$_2$}$_2$]-catalyzed [2+2+2] cycloaddition of **5q** and **5r**.

reaction conditions, the [2+2+2] cycloaddition of the phosphonate derivative **5q** easily occurred to give **6q** in 70% yield. Furthermore, the ring-closing reaction of the methyl-substituted allene **5r** proceeded without any problems to provide the desired product **6r** in 87% yield. A phenylsulfonyl group on the allenyl moiety can be regarded as a surrogate of hydrogen atom and can be easily converted into a hydrogen atom by conventional means.[28,29]

In summary, we developed a novel rhodium(I)-catalyzed intramolecular [2+2+2] cycloaddition of allene-ene-ynes to produce either tri- or tetracyclic products, containing a cyclopropane ring as the core carbon skeleton with three contiguous stereogenic centers, in a stereoselective and stereospecific manner. To the best of our knowledge, this is the first example dealing with the construction of the bicyclo-[4.1.0]heptane derivatives by taking advantage of the [2+2+2] cycloaddition, which enables easy access to a variety

of the polycyclic skeletons from simple acyclic substrates. The scope and limitations of this method as well as application to the synthesis of natural products are now in progress.

Received: September 16, 2014
Published online: October 29, 2014

Keywords: alkynes · allenes · cycloadditions · diastereoselectivity · rhodium

[1] For selected recent reviews, see: a) *Transition-Metal-Mediated Aromatic Ring Construction* (Ed.: K. Tanaka), Wiley, Hoboken, **2013**, chap. 1 – 11; b) N. Weding, M. Hapke, *Chem. Soc. Rev.* **2011**, *40*, 4525 – 4538; c) Y. Shibata, K. Tanaka, *Synthesis* **2012**, 323 – 350; d) D. L. J. Broere, E. Rujiter, *Synthesis* **2012**, 2639 – 2672.

[2] For selected recent examples, see: a) M. Petit, G. Chouraqui, P. Phansavath, C. Aubert, M. Malacria, *Org. Lett.* **2002**, *4*, 1027 – 1029; b) E. A. Anderson, E. J. Alexanian, E. J. Sorensen, *Angew. Chem. Int. Ed.* **2004**, *43*, 1998 – 2001; *Angew. Chem.* **2004**, *116*, 2032 – 2035; c) T. Shibata, T. Chiba, H. Hirashima, Y. Ueno, K. Endo, *Heteroat. Chem.* **2011**, *22*, 363 – 370.

[3] In sharp contrast to the fact that no reports dealing with the [2+2+2] cycloaddition producing a three/six-membered framework directly from acyclic substrates could be available, many examples of [2+2+2] cycloaddition using cyclic diene or triene substrates such as norbornadienes or cycloheptatrienes (homo-Diels–Alder reaction) leading to the corresponding bicyclic frameworks have been reported. For selected examples, see: a) M. Papadopoulos, M. G. Jenner, *Tetrahedron Lett.* **1985**, *26*, 3335 – 3338; b) M. Lautens, W. Tam, J. C. Lautens, L. G. Edwards, C. M. Crudden, A. C. Smith, *J. Am. Chem. Soc.* **1995**, *117*, 6863 – 6879; c) A. Tenaglia, S. Gaillard, *Org. Lett.* **2007**, *9*, 3607 – 3610.

[4] Another possible reason for the difficulty of the production of three/six-membered rings by transition-metal-catalyzed [2+2+2] cycloaddition is that the newly formed cyclopropanes would undergo the subsequent ring-opening reactions in the presence of transition-metal catalysts. For selected examples of transition-metal-catalyzed cycloaddition or cycloisomerization reactions through ring-opening of cyclopropanes, see: a) P. A. Wender, H. Takahashi, B. Witulski, *J. Am. Chem. Soc.* **1995**, *117*, 4720 – 4721; b) F. Inagaki, K. Sugikubo, Y. Miyashita, C. Mukai, *Angew. Chem. Int. Ed.* **2010**, *49*, 2206 – 2210; *Angew. Chem.* **2010**, *122*, 2252 – 2256; c) D. Shu, X. Li, M. Zhang, P. J. Robichaux, W. Tang, *Angew. Chem. Int. Ed.* **2011**, *50*, 1346 – 1349; *Angew. Chem.* **2011**, *123*, 1382 – 1385; d) X. Li, M. Zhang, D. Shu, P. J. Robichaux, S. Huang, W. Tang, *Angew. Chem. Int. Ed.* **2011**, *50*, 10421 – 10424; *Angew. Chem.* **2011**, *123*, 10605 – 10608; e) K. Sugikubo, F. Omachi, Y. Miyanaga, F. Inagaki, C. Matsumoto, C. Mukai, *Angew. Chem. Int. Ed.* **2013**, *52*, 11369 – 11372; *Angew. Chem.* **2013**, *125*, 11579 – 11582.

[5] a) I. Aujard, D. Röme, E. Arzel, M. Johansson, D. de Vos, O. Sterner, *Bioorg. Med. Chem.* **2005**, *13*, 6145 – 6150; b) M.-L. Liu, Y.-H. Duan, Y.-L. Hou, C. Li, H. Gao, Y. Dai, X.-S. Yao, *Org. Lett.* **2013**, *15*, 1000 – 1003.

[6] a) F. Inagaki, K. Sugikubo, Y. Oura, C. Mukai, *Chem. Eur. J.* **2011**, *17*, 9062 – 9065; b) C. Mukai, Y. Ohta, Y. Oura, Y. Kawaguchi, F. Inagaki, *J. Am. Chem. Soc.* **2012**, *134*, 19580 – 19583.

[7] Similar cycloaddition of allenylcyclopropane-alkynes was also developed; see Ref. [4b].

[8] For the allenylcyclopropane derivatives, we assumed the initial formation of the six-membered rhodacycle intermediate because cyclopropane has a fairly high ring-strain energy (27.5 kcal mol^{-1}); see Ref. [4b] and: J. W. Knowlton, F. D. Rossini, *J. Res. Natl. Bur. Stand.* **1949**, *43*, 113 – 115; a similar rhodacycle intermediate could be considered in the reaction of the allenylcyclopropane-alkenes, see Ref. [4e].

[9] For selected recent reviews of the C–C bond activation, see: a) M. Murakami, T. Matsuda, *Chem. Commun.* **2011**, *47*, 1100 – 1105; b) K. Ruhland, *Eur. J. Org. Chem.* **2012**, 2683 – 2706.

[10] S. Kaarsemaker, J. Coops, *Recl. Trav. Chim. Pays-Bas* **1952**, *71*, 261 – 276.

[11] For selected examples of rhodium(I)-catalyzed cycloaddition or cycloisomerization of allene-alkyne substrates, see: a) K. M. Brummond, H. Chen, P. Sill, L. You, *J. Am. Chem. Soc.* **2002**, *124*, 15186 – 15187; b) Y. Oonishi, A. Hosotani, Y. Sato, *J. Am. Chem. Soc.* **2011**, *133*, 10386 – 10389; c) Y. Oonishi, Y. Kitano, Y. Sato, *Angew. Chem. Int. Ed.* **2012**, *51*, 7305 – 7308; *Angew. Chem.* **2012**, *124*, 7417 – 7420; d) Y. Oonishi, T. Yokoe, A. Hosotani, Y. Sato, *Angew. Chem. Int. Ed.* **2014**, *53*, 1135 – 1139; *Angew. Chem.* **2014**, *126*, 1153 – 1157; e) Y. Kawaguchi, S. Yasuda, A. Kaneko, Y. Oura, C. Mukai, *Angew. Chem. Int. Ed.* **2014**, *53*, 7608 – 7612; *Angew. Chem.* **2014**, *126*, 7738 – 7742.

[12] N. Saito, T. Ichimaru, Y. Sato, *Chem. Asian J.* **2012**, *7*, 1521 – 1523.

[13] E. Haraburda, Ò. Torres, T. Parella, M. Solà, A. Pla-Quintana, *Chem. Eur. J.* **2014**, *20*, 5034 – 5045.

[14] The rhodium(I)-catalyzed intramolecular [2+2+2] cycloaddition of allene-yne-aldehydes was reported. See: Y. Oonishi, Y. Kato, Y. Sato, *Tetrahedron* **2013**, *69*, 7713 – 7718.

[15] For intramolecular [2+2+2] cycloaddition of allene-diynes with a stoichiometric amount of a cobalt complex, see: a) M. Petit, C. Aubert, M. Malacria, *Tetrahedron* **2006**, *62*, 10582 – 10593; for rhodium(I)-catalyzed reaction of allene-diynes, see: b) B. Bennacer, M. Fujiwara, S.-Y. Lee, I. Ojima, *J. Am. Chem. Soc.* **2005**, *127*, 17756 – 17767.

[16] For transition-metal-catalyzed intermolecular [2+2+2] cycloaddition of allene compounds, see: a) J.-C. Hsieh, D. K. Rayabarapu, C.-H. Cheng, *Chem. Commun.* **2004**, 532 – 533; b) T. Miura, M. Morimoto, M. Murakami, *J. Am. Chem. Soc.* **2010**, *132*, 15836 – 15838.

[17] For transition-metal-catalyzed partially intramolecular [2+2+2] cycloaddition of allene compounds, see: a) M. Shanmugasundaram, M.-S. Wu, M. Jeganmohan, C.-W. Huang, C.-H. Cheng, *J. Org. Chem.* **2002**, *67*, 7724 – 7729; b) P. Liu, S. Ma, *Org. Lett.* **2007**, *9*, 5319 – 5321; c) A. T. Brusoe, E. J. Alexanian, *Angew. Chem. Int. Ed.* **2011**, *50*, 6596 – 6600; *Angew. Chem.* **2011**, *123*, 6726 – 6730; d) N. N. Noucti, E. J. Alexanian, *Angew. Chem. Int. Ed.* **2013**, *52*, 8424 – 8427; *Angew. Chem.* **2013**, *125*, 8582 – 8585.

[18] The optimization of reaction conditions is summarized in Table S1 in the Supporting Information.

[19] We presumed that the somewhat lower yield of **6a** (72%), compared to that of **6b** (89%), might be due to the side reaction via the vinylidene-rhodium species generated from the terminal alkyne and the rhodium(I) complex. For selected examples of cyclization reactions via vinylidene rhodium intermediates, see: a) Y. Fukumoto, F. Kinashi, T. Kawahara, N. Chatani, *Org. Lett.* **2006**, *8*, 4641 – 4643; b) J. M. Joo, Y. Yuan, C. Lee, *J. Am. Chem. Soc.* **2006**, *128*, 14818 – 14819; and Ref. [11e].

[20] M. E. Jung, G. Piizzi, *Chem. Rev.* **2005**, *105*, 1735 – 1766.

[21] X-ray analysis of the derivative of **6i** unambiguously established its structure having a tetracyclic structure containing the bicyclo[4.1.0]heptene skeleton (see the Supporting Information for details).

[22] a) C. Mukai, F. Inagaki, T. Yoshida, K. Yoshitani, Y. Hara, S. Kitagaki, *J. Org. Chem.* **2005**, *70*, 7159 – 7171; b) C. Aubert, L. Fensterbank, P. Garcia, M. Malacria, A. Simonneau, *Chem. Rev.* **2011**, *111*, 1954 – 1993.

[23] It was reported that $[Rh(dppp)]SbF_6$ was effective for avoiding undesired β-hydride eliminations in some rhodium(I)-catalyzed

cyclizations. For example, see: a) L. Jiao, M. Lin, Z.-X. Yu, *Chem. Commun.* **2010**, *46*, 1059 – 1061; b) L. Jiao, M. Lin, Z.-X. Yu, *J. Am. Chem. Soc.* **2011**, *133*, 447 – 461; We carried out the reaction of **7** with 5 mol% of [Rh(dppp)]SbF_6, which resulted in the exclusive formation of **8** (94% yield).

[24] For transition-metal-catalyzed intramolecular [2+2] cycloaddition of allene-ynes, see: a) C. H. Oh, A. K. Gupta, D. I. Park, N. Kim, *Chem. Commun.* **2005**, 5670 – 5672; b) N. Saito, Y. Tanaka, Y. Sato, *Org. Lett.* **2009**, *11*, 4124 – 4126.

[25] The relative configurations of **12** and **15** were determined based on the NOE experiments (see the Supporting Information for details).

[26] In the cases of **14a** and **14b**, the cyclobutene derivatives with *Z*-alkene moiety were not obtained at all. However, negligible amounts of the cyclobutene derivatives with the *E*-alkene moiety (**13** and the *n*-pentyl analogue of **13**) were detected.

[27] The optical resolution of (±)-**5c** by HPLC provided (+)-**5c** (99% *ee*) and (−)-**5c** (99% *ee*), both of which were independently reacted under standard reaction conditions to produce (−)-**6c** (99% *ee*) and (+)-**6c** (99% *ee*), respectively, in quantitative yields. The absolute configurations of these four compounds have not yet been determined, but these two experiments unambiguously provided additional evidence that this ring-closing reaction must proceed in a stereospecific fashion.

[28] For reviews of the transformation of sulfones, see: a) C. Nájera, M. Yus, *Tetrahedron* **1999**, *55*, 10547 – 10658; b) N. S. Simpkins, *Sulfones in Organic Synthesis*, Pergamon, Oxford, **1993**.

[29] During our studies on the rhodium(I)-catalyzed ring-closing reaction, we have successfully shown that the phenylsulfonyl group on the allenyl moiety could be easily removed by conventional procedures. For example, see: a) F. Inagaki, S. Narita, T. Hasegawa, S. Kitagaki, C. Mukai, *Angew. Chem. Int. Ed.* **2009**, *48*, 2007 – 2011; *Angew. Chem.* **2009**, *121*, 2041 – 2045; b) T. Iwata, F. Inagaki, C. Mukai, *Angew. Chem. Int. Ed.* **2013**, *52*, 11138 – 11142; *Angew. Chem.* **2013**, *125*, 11344 – 11348.