

Rhodium(I)-Catalyzed Intramolecular Pauson–Khand-Type [2 + 2 + 1] Cycloaddition of Allenenes

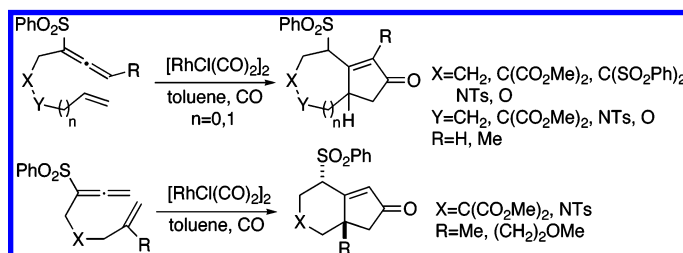
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ABSTRACT



The novel $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed [2 + 2 + 1] cycloaddition of allenenes leading to the bicyclo[4.3.0]non-1(9)-en-8-one as well as the bicyclo[5.3.0]dec-1(10)-en-9-one skeletons has been developed. This method also provides a new procedure for the construction of the bicyclo[4.3.0]non-1(9)-en-8-one skeleton having an alkyl appendage at the ring juncture, which was hardly attained in a satisfactory yield by the Pauson–Khand reaction of the corresponding enynes.

The intramolecular Pauson–Khand reaction¹ is a formal metal-mediated (or -catalyzed) [2 + 2 + 1] cycloaddition of the alkyne π -bond, the alkene π -bond, and carbon monoxide (CO) and provides the straightforward as well as powerful methodology for the construction of the cyclopentenone-fused frameworks. This ring-closing reaction has been almost exclusively limited to the use of the alkyne π -bond as one of the two carbon–carbon π -bond components, although the stepwise stoichiometric conversion² of 1-phen-

ylhepta-1,6-diene (bis-alkene derivatives) into the carbonylative bicyclo[3.3.0] compounds via the zirconacyclopentane has been reported. Wender³ very recently reported the first example of the $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed [2 + 2 + 1] cycloaddition of 1,3-dienes, alkenes, and CO, in which the 1,3-diene moiety served as the alkene π -bond⁴ instead of the alkyne π -component. On the other hand, Itoh⁵ reported an example of the $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed intramolecular [2 + 2 + 1] cycloaddition between the proximal double bond of the allenyl moiety and a vinylsilane of (8*E*)-6,6-bis-(methoxycarbonyl)-2-methyl-9-trimethylsilylnona-2,3,8-triene under 3 atm of CO resulting in the formation of 2-isopropylidenebicyclo[3.3.0]octan-3-ones. When allenenes without a silyl group on the olefin moiety were exposed to

(1) For leading reviews, see: (a) Pauson, P. L. In *Organometallics in Organic Synthesis. Aspects of a Modern Interdisciplinary Field*; de Meijere, A., tom Dieck, H., Eds.; Springer: Berlin, 1988; pp 233–246. (b) Schore, N. E. *Chem. Rev.* **1988**, 88, 1081–1119. (c) Schore, N. E. *Org. React.* **1991**, 40, 1–90. (d) Schore, N. E. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon: Oxford, 1991; Vol. 5, pp 1037–1064. (e) Schore, N. E. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Elsevier: New York, 1995; Vol. 12, pp 703–739. (f) Frühauf, H.-W. *Chem. Rev.* **1997**, 97, 523–596. (g) Jeong, N. In *Transition Metals in Organic Synthesis*; Beller, H., Bolm, C., Eds.; Wiley-VCH: Weinheim, 1998; Vol. 1, pp 560–577. (h) Geis, O.; Schmalz, H.-G. *Angew. Chem., Int. Ed.* **1998**, 37, 911–914. (i) Chung, Y. K. *Coord. Chem. Rev.* **1999**, 188, 297–341. (j) Brummond, K. M.; Kent, J. L. *Tetrahedron* **2000**, 56, 3263–3283. (k) Boñaga, L. V. R.; Krafft, M. E. *Tetrahedron* **2004**, 60, 9795–9833.

(2) Negishi, E.; Choueiry, D.; Nguyen, T. B.; Swanson, D. R.; Suzuki, N.; Takahashi, T. *J. Am. Chem. Soc.* **1994**, 116, 9751–9752.

(3) Wender, P. A.; Croatt, M. P.; Deschamps, N. M. *J. Am. Chem. Soc.* **2004**, 126, 5948–5949.

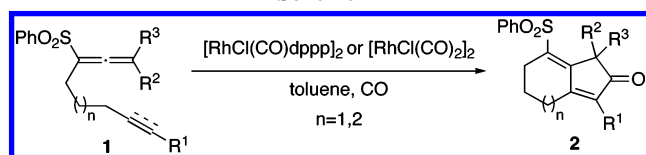
(4) Wender reported that several bis-enes failed to give the [2 + 2 + 1] products under the optimized $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed conditions.³

(5) (a) Makino, T.; Itoh, K. *Tetrahedron Lett.* **2003**, 44, 6335–6338. (b) Makino, T.; Itoh, K. *J. Org. Chem.* **2004**, 69, 395–405.

the Rh(I) catalyst, however, the ring-closing reaction proceeded in a different way to produce the seven-membered monocyclic products instead of the Pauson–Khand-type products.

Our recent interest⁶ in the development of the [RhCl(CO)₂]₂- or [RhCl(CO)dppp]₂-catalyzed intramolecular Pauson–Khand-type reaction⁷ between the alkyne π -bond and the allenyl π -bond of the phenylsulfonylallenynes **1** (allenynes) in the presence of CO led to the easy preparation of the bicyclo[4.3.0]nonadienone ($n = 1$) as well as the bicyclo[5.3.0]decadienone ($n = 2$) frameworks **2** (Scheme 1). These observations prompted us to investigate the [RhCl-

Scheme 1

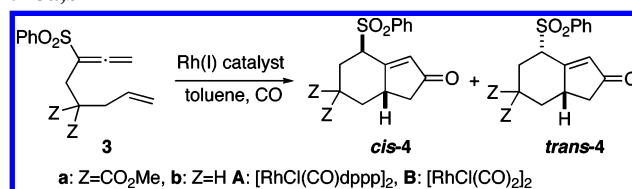


(CO)₂]₂- or [RhCl(CO)dppp]₂-catalyzed cyclocarbonylation between the alkene π -bond and the allenyl π -bond of **1** (allenenes). We report herein the preliminary results of the Rh(I)-catalyzed [2 + 2 + 1] cycloaddition of the alkene π -bond, the distal π -bond of the allenyl moiety, and CO resulting in the preparation of the bicyclo[4.3.0]nonenone and bicyclo[5.3.0]decenone skeletons.

Our initial evaluation for the Rh(I)-catalyzed cyclocarbonylation of a phenylsulfonylallenene was carried out using compounds **3a**⁸ and **3b**⁹ (Table 1). According to the previously reported conditions⁶ for the Pauson–Khand-type reaction of substrates **1** (allenynes), a solution of **3a** in toluene was refluxed for 20 h in the presence of 2.5 mol % of [RhCl(CO)dppp]₂ under an atmosphere of CO to afford the desired 2-phenylsulfonylbicyclo[4.3.0]nonenone **4a** in 64% yield as a mixture of the *cis*-**4a** and *trans*-**4a**¹⁰ in a ratio of 21:79 (entry 1).¹¹

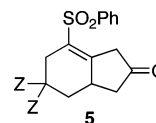
An alternative catalyst, [RhCl(CO)₂]₂, gave the ring-closed products **4a** in a rather lower yield (entry 2). A significant

Table 1. Rhodium(I)-Catalyzed [2 + 2 + 1] Cycloaddition of **3a,b**



entry	allenene	Rh(I)	mol %	CO (atm)	T (°C)	t (h)	product (%)	<i>cis:trans</i> ^a
1	3a	A	2.5	1	reflux	20	4a (64) ^b	21:79
2	3a	B	2.5	1	reflux	10	4a (22)	21:79
3	3a	A	2.5	5	120	2	4a (53)	21:79
4	3a	B	2.5	5	120	12	4a (96)	21:79
5	3b	A	2.5	5	120	3	4b (74)	62:38
6	3b	A	5	5	120	3	4b (77)	62:38

^a Ratio was determined by ¹H NMR. ^b The starting material **3a** was recovered in 30% yield.



improvement (**4a**, 96%) was observed when the ring-closing reaction of **3a** was carried out in the presence of [RhCl(CO)₂]₂ under 5 atm of CO at 120 °C (entry 4). [RhCl(CO)dppp]₂ furnished **4a** in 53% yield under 5 atm of CO (entry 3).¹² The ring-closing reaction of **3b** under 5 atm of CO with a catalytic amount of [RhCl(CO)₂]₂ also proceeded as expected to produce **4b** in 74% yield (entry 5). Increase of the loading amounts of [RhCl(CO)₂]₂ from 2.5 to 5 mol % provided **4b** in a similar yield (entry 6). The formation of **4** can be rationalized in terms of the intermediacy of the initially formed 2-phenylsulfonylbicyclo[4.3.0]non-1-en-8-one derivative **5**, which should immediately isomerize to the α,β -unsaturated ketones.

We next investigated the scope of the [RhCl(CO)₂]₂-catalyzed ring-closing reaction under 5 atm of CO using several 1,2,7-octatrienes **6**. These results are summarized in Table 2. The allenenes **6a,b**, having a heteroatom on the alkyl tether, consistently produced the corresponding bicyclic compounds **7a,b** in good yields (entries 1 and 2). The 6-alkylbicyclo[4.3.0]nonenone frameworks **7c–e** could be constructed from the 1,1-dialkylalkene derivatives **6c–e** in acceptable yields (entries 3–5), respectively. Similarly, compound **6g** with a trisubstituted allenyl moiety produced **7g** in 51% yield along with its double bond isomer **9** (36%) (entry 7). Whereas the Pauson–Khand reaction of the 2-alkyl (or phenyl)-1-hepten-6-yne are well-known to efficiently afford the 5-alkyl (or phenyl) bicyclo[3.3.0]oct-1-en-3-

(6) (a) Mukai, C.; Nomura, I.; Yamanishi, K.; Hanaoka, M. *Org. Lett.* **2002**, *4*, 1755–1758. (b) Mukai, C.; Nomura, I.; Kitagaki, S. *J. Org. Chem.* **2003**, *68*, 1376–1385. (c) Mukai, C.; Inagaki, F.; Yoshida, T.; Kitagaki, S. *Tetrahedron Lett.* **2004**, *45*, 4117–4121. (d) Mukai, C.; Inagaki, F.; Yoshida, T.; Yoshitani, K.; Hara, Y.; Kitagaki, S. *J. Org. Chem.* **2005**, *70*, 7159–7171. (e) Mukai, C.; Hirose, T.; Teramoto, S.; Kitagaki, S. *Tetrahedron* **2005**, *61*, 10983–10994.

(7) Brummond independently developed the [RhCl(CO)₂]₂-catalyzed Pauson–Khand-type [2 + 2 + 1] cycloaddition of allenynes. See: (a) Brummond, K. M.; Chen, H.; Fisher, K. D.; Kerekes, A. D.; Rickards, B.; Sill, P. C.; Geib, S. J. *Org. Lett.* **2002**, *4*, 1931–1934. (b) Brummond, K. M.; Gao, D. *Org. Lett.* **2003**, *5*, 3491–3494. (c) Brummond, K. M.; Mitasev, B. *Org. Lett.* **2004**, *6*, 2245–2248. (d) Brummond, K. M.; Curran, D. P.; Mitasev, B.; Fischer, S. *J. Org. Chem.* **2005**, *70*, 1745–1753.

(8) Padwa, A.; Filipkowski, M. A.; Meske, M.; Watterson, S. H.; Ni, Z. *J. Am. Chem. Soc.* **1993**, *115*, 3776–3777.

(9) The preparation and characterization of the unknown allenenes are described in SI.

(10) The relative stereochemistry was determined by ¹H NMR spectral considerations, in particular, by an NOE analysis.

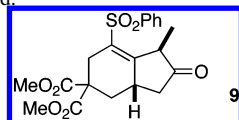
(11) The ring-closing reaction of allenenes, having the other substituent instead of a phenylsulfonyl group on the allenyl moiety, has not been examined yet. The effect of a phenylsulfonyl group in this reaction will be investigated in due course.

(12) During our investigations⁶ of the intramolecular Pauson–Khand-type [2 + 2 + 1] cycloaddition of allenynes under an atmosphere of CO, we found that [RhCl(CO)dppp]₂ generally more efficiently catalyzed the ring-closing reaction than [RhCl(CO)₂]₂, whereas the latter is much a more effective catalyst compared to the former when the reaction was carried out under CO pressure (5–10 atm). A similar behavior was observed in the ring-closing reaction of **3**.

Table 2. $[\text{RhCl}(\text{CO})_2]_2$ -Catalyzed $[2 + 2 + 1]$ Cycloaddition of 1,2,7-Trienes

entry	allenene	product	yield (%)	cis:trans ^a
1			89	71:29
2			63	82:18
3			85	0:100 ^b
4			69	0:100 ^b
5			58	0:100 ^b
6			68	—
7			51 ^c	33:67
8		—	0 ^d	—

^a Ratio was determined by ¹H NMR. ^b Isolated as a single isomer. ^c Compound **9** was also obtained in 36% yield. ^d Starting material **6h** was recovered in 50% yield.



ones,^{1,13} there are only two examples¹⁴ that described the low yield formation of the one-carbon-homologated bicyclo[4.3.0] skeletons, possessing an alkyl appendage at the ring juncture, from the acyclic enynes.¹⁵ Thus, the newly developed Pauson–Khand-type $[2 + 2 + 1]$ cycloaddition of allenenes would provide an efficient and general way for preparing the bicyclo[4.3.0] skeletons, possessing an alkyl group at the ring juncture. In sharp contrast to the alkyl derivatives **6c–e**, the phenyl congener **6f** was transformed into a different product, the bicyclo[3.2.0]heptane derivative **8**, in 68% yield (entry 6). Based on Padwa's extensive studies^{8,16} on the thermal intramolecular $[2 + 2]$ cycloaddi-

Table 3. $[\text{RhCl}(\text{CO})_2]_2$ -Catalyzed $[2 + 2 + 1]$ Cycloaddition of 1,2,8-Trienes

entry	allenene	Rh (mol %)	CO (atm)	product	yield (%)	cis:trans ^a
1	 10a Z=CO ₂ Me	2.5	5	 11a	49	15:85
2	10a	5	10	11a	73	25:75
3	10a	10	10	11a	82	35:65
4	 10b Z=SO ₂ Ph	5	10	 11b	36	60:40
5	10b	10	10	11b	47	60:40
6	 10c	10	10	 11c	33	93:7
7	 10d	10	10	 11d	73	80:20
8	 10e	10	10	 11e	30	100:0 ^b
9	 10f Z=CO ₂ Me	5	5	 12	68	—

^a Ratio was determined by ¹H NMR. ^b Isolated as a single isomer.

tion of allenenes, the formation of **8**¹⁷ would be interpreted by the thermal $[2 + 2]$ cycloaddition between the proximal π -bond of the allenyl moiety and the terminal olefin. In fact,

(13) For selected references, see: (a) Jeong, N.; Hwang, S. H.; Lee, Y.; Chung, Y. K. *J. Am. Chem. Soc.* **1994**, *116*, 3159–3160. (b) Pagenkopf, B. L.; Livinghouse, T. *J. Am. Chem. Soc.* **1996**, *118*, 2285–2286. (c) Koga, Y.; Kobayashi, T.; Narasaka, K. *Chem. Lett.* **1998**, 249–250. (d) Sugihara, T.; Yamaguchi, M. *J. Am. Chem. Soc.* **1998**, *120*, 10782–10783. (e) Hicks, F. A.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 5881–5898. (f) Krafft, M. E.; Bonaga, L. V. R.; Hirose, C. *Tetrahedron Lett.* **1999**, *40*, 9171–9175. (g) Hiroi, K.; Watanabe, T.; Kawagishi, R.; Abe, I. *Tetrahedron Asymmetry* **2000**, *11*, 797–808. (h) Fletcher, A. J.; Christie, S. D. R. *J. Chem. Soc., Perkin Trans. 1* **2000**, 1657–1668. (i) Krafft, M. E.; Wright, J. A.; Bonaga, L. V. R. *Synlett* **2005**, 71–74. (j) Tang, Y.; Deng, L.; Zhang, Y.; Dong, G.; Chen, J.; Yang, Z. *Org. Lett.* **2005**, *7*, 593–595.

(14) Bolton obtained the azabicyclo[4.3.0]nonenone derivative, having a methyl group at the ring juncture, in a less than 5% yield, whereas Ishizaki and Hoshino prepared the bicyclo[4.3.0]nonenone derivative, having a methyl group at the ring juncture, in 28% yield. See: (a) Bolton, G. L.; Hodges, J. C.; Rubin, J. R. *Tetrahedron* **1997**, *53*, 6611–6634. (b) Ishizaki, M.; Satoh, H.; Hoshino, O. *Chem. Lett.* **2002**, 1040–1041. (c) Ishizaki, M.; Satoh, H.; Hoshino, O.; Nishitani, K.; Hara, H. *Heterocycles* **2004**, *63*, 827–844.

compound **8** was obtained by simply heating in toluene at 120 °C without the Rh(I)-catalyst. The tetrasubstituted allene derivative **6h** was found to be an inadequate substrate for this ring-closing reaction, and the starting material was recovered in 50% yield (entry 8).

The application of the newly developed $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed Pauson–Khand-type $[2 + 2 + 1]$ cycloaddition of allenenes for the synthesis of the bicyclo[5.3.0]decenones was the next subject. Exposure of the 1,2,8-nonatriene **10a** to the standard ring-closing conditions (2.5 mol % of $[\text{RhCl}(\text{CO})_2]_2$, 5 atm of CO, 120 °C in toluene) afforded the bicyclo[5.3.0]decenone derivative **11a** in 49% yield as a mixture¹⁰ of the *cis*- and *trans*-isomers in the ratio 15:85 (Table 3, entry 1). Increasing both the loading amounts of the Rh(I) catalyst (5 mol %) and CO pressure (10 atm) produced an improvement in the chemical yield (73%) (entry 2). Furthermore, 10 mol % of the Rh(I) catalyst under 10 atm of CO provided **11a** in 82% yield (entry 3). Compound **10b** also furnished the ring-closed product **11b** in moderate yields (entries 4 and 5). However, the simpler 3-phenylsulfonylnona-1,2,8-triene (**10c**) gave the ring-closed product **11c** in a rather low yield (entry 6). The nitrogen atom containing substrate **10d** afforded the corresponding azabicyclo[5.3.0]decenone **11d** in 73% yield (entry 7), while the oxabicyclo congener **11e** was formed in a low yield (entry 8). The low yields for compounds **10c,e** might be attributable to the loss of the Thorpe–Ingold-type effects¹⁸ compared to those of other substrates. The 1,1-dialkylalkene derivative **10f** unexpectedly produced the bicyclo[4.2.0]nonene framework **12**¹⁹

instead of the carbonylative 7-methylbicyclo[5.3.0]decenone derivative (entry 9). Interestingly, compound **12** was not obtained when **10f** was heated for a prolonged time without the Rh(I) catalyst. Thus, the formation of **12** would tentatively be rationalized by the first isomerization of the double bond of **10f**, followed by the thermal $[2 + 2]$ cycloaddition.¹⁶ Coordination of the Rh(I) catalyst with the olefin moiety would accelerate the conversion of the terminal olefin into the internal one.

In summary, we have described the novel $[\text{RhCl}(\text{CO})_2]_2$ -catalyzed intramolecular $[2 + 2 + 1]$ cycloaddition of 3-phenylsulfonyl-1,2,7-octatrienes leading to the formation of the bicyclo[4.3.0]non-1(9)-en-8-one, in which the distal double-bond of the allenyl moiety exclusively served as a π -component. This method not only was shown to be applicable to the construction of the one-carbon homologated bicyclo[5.3.0]dec-1(10)-en-9-one skeleton but also provided a new entry for the construction of the bicyclo[4.3.0]non-1(9)-en-8-one skeleton having an alkyl appendage at the ring juncture, which was hardly attained in a satisfactory yield by the Pauson–Khand reaction of the corresponding enynes. Determining the scope and limitations of this method as well as application to the synthesis of natural products are now in progress.

Acknowledgment. This work was supported in part by a Grant-in Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan, for which we are thankful.

Supporting Information Available: General procedures for the $[2 + 2 + 1]$ cycloaddition and preparation of sulfonylallenenes, characterization data for all new compounds, and ¹H and ¹³C NMR spectra for compounds **6d,e**, **7b,d,e,g**, **10c,e,f**, and **11e**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(19) Padwa^{16a} reported that the thermolysis of 5,5-bis(methoxycarbonyl)-3-phenylsulfonylnona-1,2,8-triene and 3,5,5-tris(phenylsulfonyl)nona-1,2,8-triene in refluxing xylene afforded the monocyclic eight-membered products in high yields instead of the bicyclo[5.2.0]nonenes.

(15) A few precedents dealing with the construction of the more complexed ring-fused cyclic compounds (including a bicyclo[4.3.0]nonenone framework) from enynes are available. See: (a) Corlay, H.; Fouquet, E.; Magnier, E.; Motherwell, W. B. *Chem. Commun.* **1999**, 183–184. (b) Ishizaki, M.; Iwahara, K.; Niimi, Y.; Satoh, H.; Hoshino, O. *Tetrahedron* **2001**, 57, 2729–2738. (c) Magnus, P.; Fielding, M. R.; Wells, C.; Lynch, V. *Tetrahedron Lett.* **2002**, 43, 947–950.

(16) (a) Padwa, A.; Meske, M.; Murphree, S.; Watterson, S. H.; Ni, Z. *J. Am. Chem. Soc.* **1995**, 117, 7071–7080. (b) Padwa, A.; Lipka, H.; Watterson, S. H.; Murphree, S. S. *J. Org. Chem.* **2003**, 68, 6238–6250.

(17) No bicyclo[3.2.0] compounds, such as compound **8**, could be detected except during the reaction of **6f**.

(18) For a recent review, see: Jung, M. E.; Piizzi, G. *Chem. Rev.* **2005**, 105, 1735–1766.