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Enantioselective Intramolecular [2 + 2 + 2] Cycloaddition of Enediynes for the Synthesis of Chiral Cyclohexa-1,3-dienes

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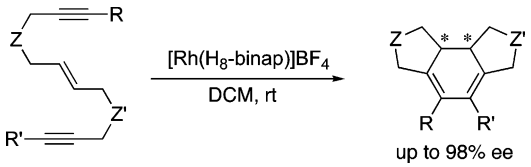
Received April 11, 2007

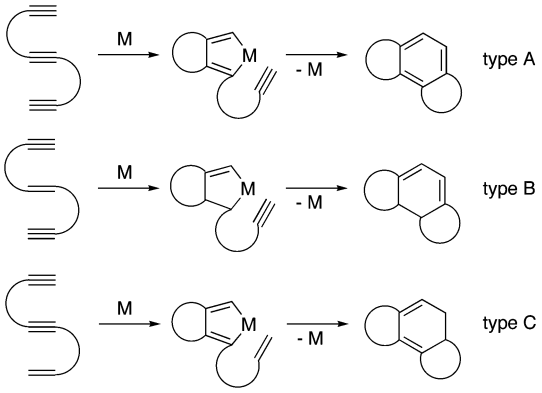


The enantioselective intramolecular [2 + 2 + 2] cycloaddition of various enediynes, where two acetylenic moieties are connected by a trans-olefinic moiety, gave chiral tricyclic cyclohexa-1,3-dienes using Rh-H_8-BINAP catalyst. In the case of carbon-atom-tethered enediynes, enantioselectivity was generally good-to-high regardless of the substituents on their alkyne termini. In contrast, with heteroatom-tethered enediynes, appropriate substituents were required to induce the oxidative coupling of alkyne and alkene moieties before that of two alkyne moieties, which would be important for highly enantioselective intramolecular cycloaddition.

Introduction

The transition-metal-catalyzed [2 + 2 + 2] cycloaddition of C2-unsaturated motifs, such as alkynes and alkenes, is a powerful and reliable method for the synthesis of a six-membered carbon skeleton.[1] There are several types of cycloadditions, including intermolecular and intramolecular reactions. Among the latter reactions (Scheme 1), the cycloaddition of triynes is a well-known protocol for the synthesis of substituted benzene derivatives (type A), and various transition-metal complexes including those of Rh,[2] Ni,[3] Pd,[4] Ru,[5] Co,[6] Mo,[7] and Fe[8] have been shown to be efficient catalysts. Three examples

SCHEME 1. Types of Intramolecular [2 + 2 + 2] Cycloadditions



(1) Recent reviews: (a) Yamamoto, Y. *Curr. Org. Chem.* **2005**, *9*, 503−509. (b) Kotha, S.; Brahmachary, E.; Lahiri, K. *Eur. J. Org. Chem.* **2005**, 4741−4761. (c) Chopade, P. R.; Louie, J. *Adv. Synth. Catal.* **2006**, *348*, 2307−2327.

(2) (a) Grigg, R.; Scott, R.; Stevenson, P. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1357−1364. (b) Ojima, I.; Vu, A. T.; McCullagh, J. V.; Kinoshita, A. *J. Am. Chem. Soc.* **1999**, *121*, 3230−3231. (c) Witulski, B.; Alayrac, C. *Angew. Chem., Int. Ed.* **2002**, *41*, 3281−3284. (d) Kinoshita, H.; Shinokubo, H.; Oshima, K. *J. Am. Chem. Soc.* **2003**, *125*, 7784−7785.

(3) Bhatarah, P.; Smith, E. H. *J. Chem. Soc., Perkin Trans. 1* **1992**, 2163−2168.

(4) (a) Negishi, E.; Harring, L. S.; Owczarczyk, Z.; Mohamud, M. M.; Ay, M. *Tetrahedron Lett.* **1992**, *33*, 3253−3256. (b) Yamamoto, Y.; Nagata, A.; Arikawa, Y.; Tatsumi, K.; Itoh, K. *Organometallics* **2000**, *19*, 2403−2405. (c) Yamamoto, Y.; Nagata, A.; Nagata, H.; Ando, Y.; Arikawa, Y.; Tatsumi, K.; Itoh, K. *Chem.−Eur. J.* **2003**, *9*, 2469−2483. (d) Pla-Quintana, A.; Roglans, A.; Torrent, A. *Organometallics* **2004**, *23*, 2762−2767.

(5) (a) Peters, J.-U.; Blechert, S. *Chem. Commun.* **1997**, 1983−1984. (b) Hoven, G. B.; Efskind, J.; Rømming, C.; Undheim, K. *J. Org. Chem.* **2002**, *67*, 2459−2463. (c) Yamamoto, Y.; Arakawa, T.; Ogawa, R.; Itoh, K. *J. Am. Chem. Soc.* **2003**, *125*, 12143−12160.

(6) (a) Stará, I. G.; Starý, I.; Kollárovič, A.; Teplý, F.; Šaman, D.; Tichý, M. *J. Org. Chem.* **1998**, *63*, 4046−4050. (b) Son, S. U.; Paik, S.-J.; Lee, S. I.; Chung, Y. K. *J. Chem. Soc., Perkin Trans. 1* **2000**, 141−143. (c) Sugihara, T.; Wakabayashi, A.; Nagai, Y.; Takao, H.; Imagawa, H.; Nishizawa, M. *Chem. Commun.* **2002**, 576−577. (d) Teplý, F.; Stará, I. G.; Starý, I.; Kollárovičc, A.; Šaman, D.; Vyskočil, S.; Fiedler, P. *J. Org. Chem.* **2003**, *68*, 5193−5197.

(7) Nishida, M.; Shiga, H.; Mori, M. *J. Org. Chem.* **1998**, *63*, 8606−8608.

10.1021/jo070762d CCC: $37.00
Published on Web 07/18/2007

of an enantioselective reaction have also been reported: a helically chiral compound was obtained using a chiral Ni catalyst,[9] *ortho*-diarylbenzenes with two axial chiralities were provided using a chiral Ir catalyst,[10] and planar chiral metacyclophanes were obtained using a chiral Rh catalyst.[11] Compared with the abundant information regarding triynes, there are few examples of enediynes, including yne-ene-ynes (type B) and yne-yne-enes (type C).[12] Yamamoto and co-workers reported the Pd-catalyzed reaction of an oxygen-tethered yne-ene-yne, which gave a mixture of cyclohexa-1,3- and 1,4-dienes.[13] Pd catalyst could also be used in the cycloaddition of yne-yne-enes.[13] While the cobalt-mediated reaction of yne-yne-enes,[14] including a diastereoselective version,[15] has been reported, to the best of our knowledge the catalytic and enantioselective cycloaddition of enediynes remains unexplored.[16,17]

Recently, Roglans and co-workers reported a Rh-catalyzed intramolecular [2 + 2 + 2] cycloaddition, where macrocyclic enediynes with an *E*-olefinic moiety gave *dl* cycloadducts and those with a *Z*-olefinic moiety gave meso cycloadducts.[18] Therefore, the enantioselective cycloaddition of an acyclic enediyne with an *E*-olefinic moiety using a chiral catalyst would give a tricyclic cyclohexa-1,3-diene with two chiral carbon centers via a bicyclic metallacyclopentene (Scheme 2). If a symmetrical substrate (R = R′) were used, a C_2 symmetrical compound would be obtained.

We report here that the cationic Rh-H_8-BINAP complex catalyzes an enantioselective [2 + 2 + 2] cycloaddition of symmetrical and unsymmetrical (*E*)-enediynes. The different enantioselectivities of this cycloaddition between a reaction pathway via alkyne−alkene coupling and that via alkyne−alkyne coupling are also discussed.

SCHEME 2. Enantioselective [2 + 2 + 2] Cycloaddition of (*E*)-Enediynes

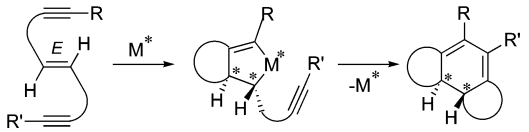
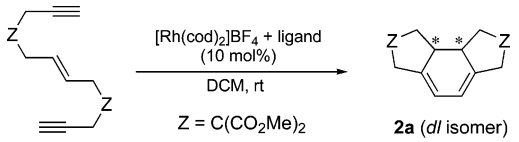


TABLE 1. Screening of Various Chiral Ligands



entry	ligand	time/h	yield/%	ee/%
1	(*S*)-BINAP	24	59	19
2	(*S*)-tolBINAP	24	15	1
3	(*S*)-H_8-BINAP	1/4	75	76
4[a]	(*S*,*S*)-BDPP	3	NR	
5[a]	(*S*,*S*)-MeDUPHOS	3	NR	

[a] DCE was used as solvent, and the reaction temperature was gradually raised to reflux.

Results and Discussion

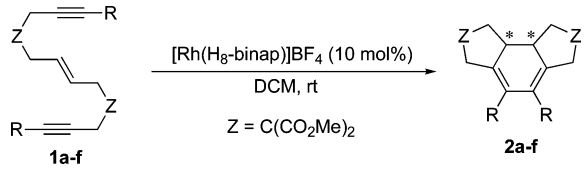
We chose carbon-atom-tethered symmetrical enediyne **1a** as a model substrate and used it in the reaction using cationic rhodium complexes with various chiral diphosphine ligands in dichloromethane (DCM) at room temperature (Table 1).[19] When BINAP was used, [2 + 2 + 2] cycloadduct **2a** was obtained as a *dl* isomer, as expected; however, its enantiomeric excess was low (entry 1). In the case of tolBINAP, which was an efficient chiral ligand for the enantioselective intermolecular [2 + 2 + 2] cycloaddition of enynes with alkynes,[20] the reaction proceeded sluggishly, and almost no enantioselectivity was observed (entry 2). In contrast, H_8-BINAP was found to be an appropriate ligand for the present reaction: enediyne **1a** was consumed within 15 min and cycloadduct **2a** was obtained in good yield and ee (entry 3). Rh-MeDUPHOS and -BDPP complexes showed almost no catalytic activity (entries 4 and 5).

When a preliminarily isolated chiral rhodium complex, [Rh(cod){(*S*)-H_8-binap}]BF_4, was used, slight increases in yield and ee were observed (Table 2, entry 1). Under these reaction conditions, carbon-atom-tethered symmetrical (*E*)-enediynes with various substituents on their termini were examined.[21] In the case of methoxycarbonyl- and benzyloxymethyl-substituted

(8) Saino, N.; Kogure, D.; Okamoto, S. *Org. Lett.* **2005**, *7*, 3065−3067.
(9) Stará, I. G.; Starý, I.; Kollárovič, A.; Teplý, F.; Vyskočil, Š.; Šaman, D. *Tetrahedron Lett.* **1999**, *40*, 1993−1996.
(10) Shibata, T.; Tsuchikama, K.; Otsuka, M. *Tetrahedron: Asymmetry* **2006**, *17*, 614−619.
(11) Tanaka, K.; Sagae, H.; Toyoda, K.; Noguchi, K.; Hirano, M. *J. Am. Chem. Soc.* **2007**, *129*, 1522−1523.
(12) Carbonylative carbocyclization of yne-yne-enes was already reported: Ojima, I.; Lee, S.-Y. *J. Am. Chem. Soc.* **2000**, *122*, 2385−2386.
(13) Yamamoto, Y.; Kuwabara, S.; Ando, Y.; Nagata, H.; Nishiyama, H.; Itoh, K. *J. Org. Chem.* **2004**, *69*, 6697−6705.
(14) Slowinski, F.; Aubert, C.; Malacria, M. *Adv. Synth. Catal.* **2001**, *343*, 64−67.
(15) (a) Slowinski, F.; Aubert, C.; Malacria, M. *Tetrahedron Lett.* **1999**, *40*, 5849−5852. (b) Slowinski, F.; Aubert, C.; Malacria, M. *J. Org. Chem.* **2003**, *68*, 378−386.
(16) A pioneering work of Co-mediated cycloaddition of two alkynes and an alkene for the synthesis of cyclohexa-1,3-dienes: Wakatsuki, T.; Kuramitsu, T.; Yamazaki, H. *Tetrahedron Lett.* **1974**, *15*, 4549−4552.
(17) Catalytic intermolecular [2 + 2 + 2] cycloadditions of two alkyne and an alkene moieties for the synthesis of cyclohexa-1,3-dienes: (a) Kezuka, S.; Tanaka, S.; Ohe, T.; Nakaya, Y.; Takeuchi, R. *J. Org. Chem.* **2006**, *71*, 543−552. (b) Wu, M.-S.; Rayabarapu, D. K.; Cheng, C.-H. *Tetrahedron* **2004**, *60*, 10005−10009. (c) Sambaiah, T.; Li, L.-P.; Huang, D.-J.; Lin, C.-H.; Rayabarapu, D. K.; Cheng, C.-H. *J. Org. Chem.* **1999**, *64*, 3663−3670. (d) Yamamoto, Y.; Kitahara, H.; Ogawa, R.; Kawaguchi, H.; Tatsumi, K.; Itoh, K. *J. Am. Chem. Soc.* **2000**, *122*, 4310−4319. (e) Ikeda, S.; Kondo, H.; Mori, N. *Chem. Commun.* **2000**, 815−816. (f) Mori, N.; Ikeda, S.; Sato, Y. *J. Am. Chem. Soc.* **1999**, *121*, 2722−2727. (g) Yamamoto, Y.; Kitahara, H.; Hattori, R.; Itoh, K. *Organometallics* **1998**, *17*, 1910−1912. (h) Yamamoto, Y.; Kitahara, H.; Ogawa, R.; Itoh, K. *J. Org. Chem.* **1998**, *63*, 9610−9611. (i) Ikeda, S.; Watanabe, H.; Sato, Y. *J. Org. Chem.* **1998**, *63*, 7026−7029. (j) Ikeda, S.; Mori, N.; Sato, Y. *J. Am. Chem. Soc.* **1997**, *119*, 4779−4780. (k) Balaich, G. J.; Rothwell, I. P. *J. Am. Chem. Soc.* **1993**, *115*, 1581−1583. (l) Zhou, Z.; Costa, M.; Chiusoli, G. P. *J. Chem. Soc., Perkin Trans. 1* **1992**, 1399−1406. (m) Zhou, Z.; Battaglia, L. P.; Chiusoli, G. P.; Costa, M.; Nardelli, M.; Pelizzi, C.; Predieri, G. *J. Chem. Soc., Chem. Commun.* **1990**, 1632−1634. (n) Suzuki, H.; Itoh, K.; Ishii, Y.; Simon, K.; Ibers, J. A. *J. Am. Chem. Soc.* **1976**, *98*, 8494−8500.
(18) Torrent, A.; González, I.; Pla-Quintana, A.; Roglans, A. *J. Org. Chem.* **2005**, *70*, 2033−2041.

(19) Tanaka reported cationic Rh-BINAP derivative complexes as efficient catalysts for intermolecular [2 + 2 + 2] cycloaddition of alkynes. See: Tanaka, K.; Shirasaka, K. *Org. Lett.* **2003**, *5*, 4697−4699.
(20) (a) Evans, P. A.; Lai, K. W.; Sawyer, J. R. *J. Am. Chem. Soc.* **2005**, *127*, 12466−12467. (b) Shibata, T.; Arai, Y.; Tahara, Y. *Org. Lett.* **2005**, *7*, 4955−4957.
(21) When (*Z*)-enediyne **1a** was examined under the same reaction conditions, an ene-type product derived from the enyne moiety was a major product and [2 + 2 + 2] cycloadduct could not be detected. For enantioselective ene-type reaction of 1,6-enynes with (*Z*)-olefinic moiety using chiral Rh catalysts, see: (a) Cao, P.; Zhang, X. *Angew. Chem., Int. Ed.* **2000**, *39*, 4104−4106. (b) Lei, A.; He, M.; Zhang, X. *J. Am. Chem. Soc.* **2002**, *124*, 8198−8199. (c) Lei, A.; Waldkirch, J. P.; He, M.; Zhang, X. *Angew. Chem., Int. Ed.* **2002**, *41*, 4526−4529.
(22) Only a trace amount of cycloadduct **2d** was detected at room temperature for 24 h.

TABLE 2. [2 + 2 + 2] Cycloaddition of Carbon-Tethered Symmetrical Enediynes

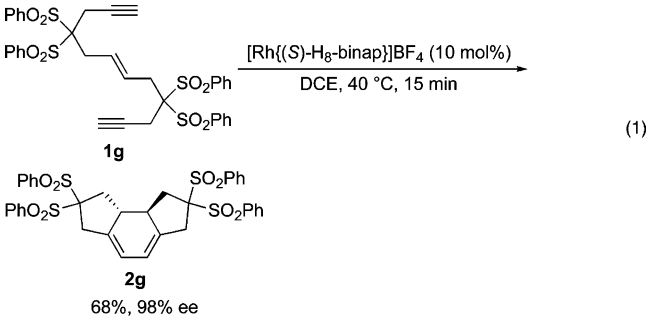


entry	R		time/h	yield/%	ee/%
1	H	**1a**	1/4	81 (**2a**)	78
2	CO_2Me	**1b**	1	72 (**2b**)	98
3	CH_2OBn	**1c**	6	63 (**2c**)	98
4[a]	Me	**1d**	24	81 (**2d**)	97
5[a]	Br	**1e**	24	48 (**2e**)	91
6[a,b]	Ph	**1f**	24	41 (**2f**)	95

[a] DCE was used as solvent at 60 °C. [b] The amount of the catalyst was 20 mol %.

enediynes **1b** and **1c**, the reaction proceeded at room temperature and the enantioselectivity was extremely high (entries 2 and 3). Me-substituted enediyne **1d** was less reactive than enediynes **1b** and **1c**, and a higher reaction temperature was required;[22] however, the ee of cycloadduct **2d** was still extremely high (entry 4). On the basis of the reaction temperature and time, the reactivity of enediynes depending on the substituents of their alkyne termini was in the order methoxycarbonyl > benzyloxymethyl > methyl. Bromo-substituted enediyne **1e** also underwent the cycloaddition, and 2,3-dibromocylcohexa-1,3-diene **2e** was obtained (entry 5). A phenyl substituent retarded the cycloaddition and harsher conditions were required, but cycloadduct **2f** was obtained in high ee (entry 6).

Next, we examined enediyne **1g** which has geminal phenylsulfonyl groups on its tethers (eq 1): in contrast to enediyne **1a** (Table 2, entry 1), extremely high ee was achieved despite the lack of a substituent on its alkyne termini. Moreover, cycloadduct **2g** was determined to be an (*R*,*R*)-isomer by X-ray crystallographic measurements (Supporting Information).

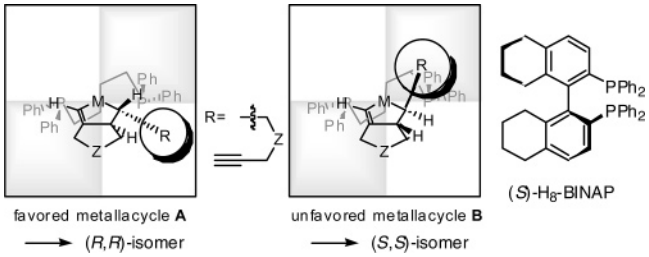


(1)

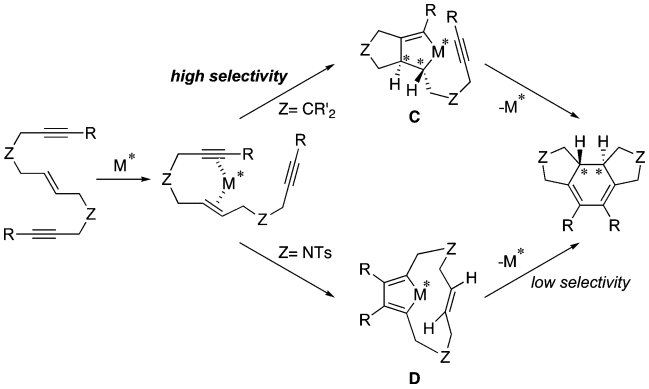
Scheme 3 shows a possible explanation for the asymmetric induction of the (*R*,*R*)-isomer by the Rh-(*S*)-H_8-BINAP catalyst. Two asymmetric carbon atoms would be induced at the formation of metallacyclopentene derived from an enyne moiety of enediyne. Because of the equatorial phenyls on phosphorus atoms of H_8-BINAP, the first and third quadrants are congested. As a result, metallacyclopentene **A**, where the R substituent is located at the fourth quadrant, is more favorable than metallacyclopentene **B**, where steric repulsion between R and phenyl groups exists.

Unsymmetrical enediyne **1h**, which has methoxycarbonyl and methyl groups on its termini, was also a good substrate, and

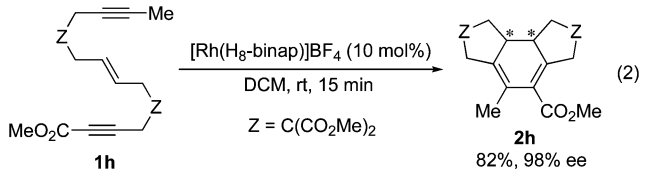
SCHEME 3. Possible Explanation of Asymmetric Induction and the Structure of H_8-BINAP



SCHEME 4. Possible Explanation for the Different Enantioselectivity

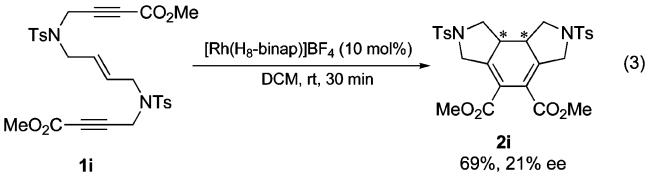


the corresponding cycloadduct **2h** was obtained in good yield and extremely high ee (eq 2).



(2)

Next, we examined nitrogen-tethered enediyne **1i** with methoxycarbonyl groups on its termini, which gave the best enantioselectivity in the case of carbon-tethered enediynes (Table 2, entry 2): the substrate was completely consumed within 30 min and the corresponding cycloadduct **2i** was obtained, but its enantiomeric excess was very low (eq 3).



(3)

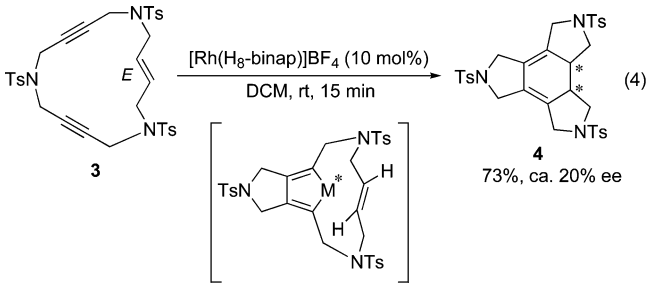
We assumed that the different enantioselectivity depending on the structure of tethers derives from the reaction pathway (Scheme 4): π-complexation of the metal catalyst to the enyne moiety of enediyne would be the beginning of the present cycloaddition. In the case of carbon-tethered enediyne, the oxidative coupling would proceed with high enantioselectivity to give bicyclic metallacyclopentene **C**, where two chiral carbon centers are generated. The subsequent intramolecular alkyne insertion along with reductive elimination gives a tricyclic cyclohexa-1,3-diene. In contrast, in the case of nitrogen-tethered enediyne, the oxidative coupling of two distant alkyne moieties would proceed before that of the enyne moiety to give a bicyclic

TABLE 3. [2 + 2 + 2] Cycloaddition of Nitrogen-Tethered Enediynes

entry	R	R′		time/h	yield/%	ee/%
1	CH_2OBn	CH_2OBn	**1j**	2	75 (**2j**)	51
2	Me	CH_2OBn	**1k**	2	71 (**2k**)	71
3	Bu	Bu	**1l**	4	90 (**2l**)	89

metallacyclopentadiene **D** because nitrogen tether activates the alkynes more than carbon tether. The enantioselectivity of the subsequent intramolecular alkene insertion is expected to be very low, and the corresponding cycloadduct would be obtained in poor ee.

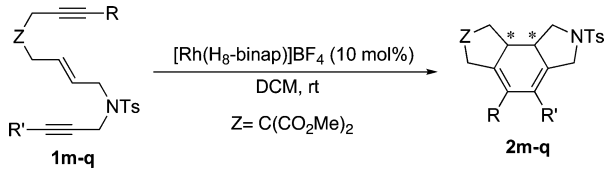
To ascertain the validity of the above speculation, we subjected cyclic enediyne **3** with an *E*-olefinic moiety[18] to enantioselective [2 + 2 + 2] cycloaddition, where oxidative coupling of a diyne moiety would proceed predominantly before that of an enyne moiety. Under the same reaction conditions as those of acyclic enediynes, tetracyclic cyclohexa-1,3-diene **4** was obtained in good yield, but its enantiomeric excess was very low, as expected (eq 4).



These results imply that the selective formation of metallacyclopentene from an enyne moiety of an enediyne would induce high enantioselectivity. To suppress the oxidative coupling of two alkyne moieties, we introduced appropriate substituents to the alkyne termini of enediyne, which would decrease the reactivity of alkyne moieties (Table 3). When enediyne **1j** with benzyloxymethyl groups was used, enantiomeric excess of cycloadduct **2j** was drastically increased (entry 1). The introduction of alkyl group(s) further improved the enantioselectivity (entries 2 and 3): in the case of enediyne **1l** with two butyls on its alkyne termini, the enantiomeric excess reached almost 90%.[23]

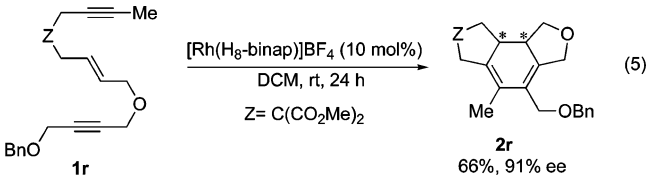
We further examined unsymmetrical enediynes possessing carbon and nitrogen tethers (Table 4). In the case of enediyne **1m** with unsubstituted alkyne termini, enantioselectivity was low, probably because terminal alkynes are very reactive and the oxidative coupling of two alkyne moieties would proceed predominantly before that of the enyne moiety (entry 1). In fact, the introduction of a methyl group decreased the reactivity of the alkyne of the nitrogen-tethered enyne moiety and enantioselectivity was improved (entry 2). When a methoxycarbonyl group was introduced to the alkyne terminus of the carbon tether, the oxidative coupling of two alkyne moieties could be further impaired and the ee of cycloadduct **2o** exceeded 90% (entries 3 and 4). Nitrogen-tethered enynes are generally more reactive than carbon-tethered enynes, but the introduction of an ester functionality increased the reactivity of alkyne and oxidative coupling would mainly occur at the carbon-tethered enyne moieties in enediynes **1o** and **1p**. Methyl groups at alkyne termini sufficiently interfered with alkyne−alkyne oxidative coupling, and extremely high enantioselectivity was achieved (entry 5).

TABLE 4. [2 + 2 + 2] Cycloaddition of Unsymmetrical Enediynes with Carbon and Nitrogen Tethers



entry	R	R′		time/h	yield/%	ee/%
1	H	H	**1m**	1/4	41 (**2m**)	15
2	H	Me	**1n**	1	55 (**2n**)	64
3	CO_2Me	Me	**1o**	1/4	66 (**2o**)	91
4	CO_2Me	Ph	**1p**	1/4	68 (**2p**)	91
5	Me	Me	**1q**	1/2	>99 (**2q**)	97

Enediyne **1r** with carbon and oxygen tethers could also be transformed into the corresponding chiral tricyclic product **2r** in high ee (eq 5).



Conclusions

We here developed an enantioselective intramolecular [2 + 2 + 2] cycloaddition of various enediynes using Rh-H_8-BINAP catalyst. The reaction of carbon-tethered enediynes proceeded with high enantioselectivity to give tricyclic cyclohexa-1,3-dienes. In the case of nitrogen-tethered enediynes, the choice of substituents on the alkyne termini is very important for high enantioselectivity to prevent alkyne−alkyne oxidative coupling of enediynes prior to alkyne−alkene coupling. Unsymmetrical enediynes with carbon and heteroatom tethers were also transformed into [2 + 2 + 2] cycloadducts in high ee.

Experimental Section

General. Anhydrous DCM and 1,2-dichloroethane (DCE) are commercially available, and they were dried over molecular sieves 4 Å (MS 4 Å) and degassed by argon bubbling before use. All reactions were examined under an argon atmosphere. NMR spectra were measured using TMS as an internal standard, and $CDCl_3$ was used as a solvent.

Typical Experimental Procedure for the Enantioselective Intramolecular [2 + 2 + 2] Cycloaddition of Enediyne 1a (Table 2, Entry 1). Under an atmosphere of argon, [Rh(cod)(H_8-binap)]-BF_4 (10.0 mg, 0.010 mmol) was stirred in DCM (1.0 mL) at room temperature. The flask was purged with hydrogen gas, and the solution was stirred for a further 30 min. After the solvent and

(23) We examined enediyene **1l** with two butyls because an enediyene with two methyls on its alkyne termini gave insoluble products and their structures could not be determined.

hydrogen were excluded under reduced pressure, argon gas was introduced. To the flask was added DCM (0.2 mL), and the solution was stirred; then enediyne **1a** (39.2 mg, 0.10 mmol) in DCM (0.8 mL) was added, and the mixture was stirred at ambient temperature for 15 min. The solvent was removed under reduced pressure, and the resulting crude products were purified by thin-layer chromatography to give pure cycloadduct **2a** (31.8 mg, 0.081 mmol, 81%).

(*E*)-Tetramethyldodec-6-ene-1,11-diyne-4,4,9,9-tetracarboxylate (1a): White solid. mp 102 °C (hexane/Et_2O); IR (CH_2Cl_2) 3286, 2956, 1737, 1201, 690 cm^{-1}; ^1H NMR δ = 2.02 (t, J = 2.7 Hz, 2H), 2.76−2.78 (m, 8H), 3.74 (s, 12H), 5.40−5.44 (m, 2H); ^{13}C NMR δ = 22.6, 35.3, 52.8, 56.8, 71.5, 78.8, 128.6, 170.1; Anal. Calcd for $C_{20}H_{24}O_8$: C, 61.22; H, 6.16. Found: C, 61.31; H, 6.27.

***trans*-Tetramethyl-1,3,6,8,8a,8b-hexahydro-*as*-indacene-2,2,7,7-tetracarboxylate (2a):** White solid. mp 81 °C (hexane/Et_2O); IR (CH_2Cl_2) 2954, 1731, 1280, 1218, 764 cm^{-1}; ^1H NMR δ = 1.92 (dd, J = 11.0, 13.1 Hz, 2H), 2.38−2.44 (m, 2H), 2.67 (dd, J = 5.5, 13.1 Hz, 2H), 2.91 (d, J = 17.7 Hz, 2H), 3.16 (d, J = 17.7 Hz, 2H), 3.72 (s, 6H), 3.74 (s, 6H), 5.79 (s, 2H); ^{13}C NMR δ = 37.9, 40.0, 44.5, 52.8, 52.8, 59.6, 117.3, 140.6, 172.0, 172.0; Anal. Calcd for $C_{20}H_{24}O_8$: C, 61.22; H, 6.16. Found: C, 61.23; H, 6.16. $[\alpha]^{25}_D$ 42.0° (*c* 1.36, $CHCl_3$, 78% ee). The ee was determined by HPLC analysis using a chiral column (Daicel Chiralcel Doubly Arrayed OD-H: 4 × 250 mm, 254 nm UV detector, rt, eluent: 5% 2-propanol in hexane, flow rate: 1.0 mL/min, retention time: 21 min for minor isomer and 23 min for major isomer).

Acknowledgment. We thank Takasago International Corp. for the gift of H_8-BINAP. This research was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Supporting Information Available: Spectral data for all new compounds and CIF file. This material is available free of charge via the Internet at http://pubs.acs.org.

JO070762D