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Ruthenium-Catalyzed Cyclization of Alkyne−Epoxide Functionalities through Alternation of the Substituent and Structural Skeleton of Epoxides

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Treatment of 1-(*o*-ethynylphenyl)-2-alkyl-2-aryl epoxides with $TpRuPPh_3(CH_3CN)_2PF_6$ catalyst (10 mol %) in hot toluene (100 °C, 12 h) led to an atypical cyclization and gave 1-aryl-2-alkyl-1*H*-indene derivatives and carbon monoxide efficiently. The cyclization of 1-*cis*-enynyl-2-alkyl epoxides with this catalyst in hot toluene (10 mol %, 100 °C, 12 h) gave 2,5-disubstituted phenols in 45−72% yields. Under the same conditions, 1-*cis*-enynyl- 2,2-dialkyl epoxides and 1-*cis*-enynyl- 2-alkyl-2-aryl epoxides gave the corresponding 6,6-disubstituted cyclohexa-2,4-dien-1-ones in good yields (85−91%). Mechanisms for these new cyclization reactions are proposed on the basis of trapping experiments and isotope labeling experiments. The formation of 1*H*-indene products likely involves ruthenium−acyl intermediates whereas cyclohexa-2,4-dien-1-ones are thought to derive from ruthenium−ketene intermediates.

Introduction

Transition-metal-catalyzed cyclization is a powerful tool for the construction of complex carbocyclic and heterocyclic molecules.[1,2] The reaction generally involves formation of two or three carbon−carbon bonds among molecules of π-type such as alkene, alkyne, 1,3-diene, methylenecyclopropane, carbon monoxide, ketone, aldehyde, allene, and imine. Although the hybridization of an epoxide molecule lies between sp² and sp³ character,[3] metal-mediated coupling reaction on organic epoxides is less studied.[4,5] Several metal salts effect the coupling of epoxide with alkyne via a one-electron radical process[6] or acid-mediated ring opening of epoxides,[7] but the

reaction generally requires an excess amount of metal or Lewis acid reagents. Only a few examples have been reported for catalytic epoxide−alkyne coupling reaction.[4,5]

Recently, we reported[8] a cascade alkyne−epoxide cyclization of (*o*-ethynyl)phenyl epoxides catalyzed by $TpRuPPh_3(CH_3CN)_2PF_6$.[9] This cyclization led to a complete oxygen transfer from epoxide to terminal alkyne to give cationic ruthenium ketene−alkene intermediate (**I**), further leading to intramolecular cyclization.[8] The reaction products are highly dependent on the epoxide substituents: 1,2-disubstituted epoxides gave 2-naphthol product **A** whereas 1,2,2-trisubstituted epoxides afforded 1-alkylidene-2-indanones **B** (Scheme 1). These two cyclized products arise from attack of the alkene of intermediate **I** at the tethered ketene functionality via 6-*endo-dig* and 5-*endo-dig* cyclizations, respectively. For such a cationic cyclization, we envisage that the substituents of epoxide substrate are crucial for the cyclization chemoselectivity because they affect the location of cationic charge of reaction intermediates **I**. In this continuing work, we discovered new patterns of alkyne−epoxide cyclization

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(5) Molinaro, C.; Jamison, T. F. *J. Am. Chem. Soc.* **2003**, *125*, 8076.

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(7) (a) Chou, W.-N.; White, J. B. *Tetrahedron Lett.* **1991**, *32*, 7637. (b) Gaebert, C.; Mattaay, I. *Tetrahedron Lett.* **1997**, *53*, 14297. (c) Palomino, E.; Schaap, A. P.; Heeg, M. J. *Tetrahedron Lett.* **1989**, *30*, 6801. (d) Madhushaw, R. J.; Li, C.-L.; Shen, K.-H.; Hu, C.-C.; Liu, R.-S. *J. Am. Chem. Soc.* **2001**, *123*, 7427.

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(9) For catalytic reactions that use this ruthenium catalyst, see: (a) Yeh, K.-L.; Liu, B.; Lo, C.-Y.; Liu, R.-S. *J. Am. Chem. Soc.* **2002**, *124*, 6510. (b) Datta, S.; Chang, C.-L.; Yeh, K.-L.; Liu, R.-S. *J. Am. Chem. Soc.* **2003**, *125*, 9294. (c) Shen, H.-C.; Pal, S.; Lian, J.-J.; Liu, R.-S. *J. Am. Chem. Soc.* **2003**, *125*, 15762. (d) Lo, C.-Y.; Guo, H.-Y.; Lian, J.-J.; Liu, R.-S. *J. Org. Chem.* **2002**, *67*, 3930. (e) Chang, C.-L.; Kumar, M. P.; Liu, R.-S. *J. Org. Chem.* **2004**, 69, 2793.

SCHEME 1
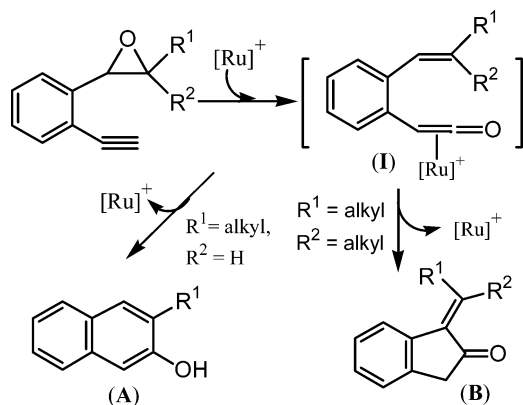
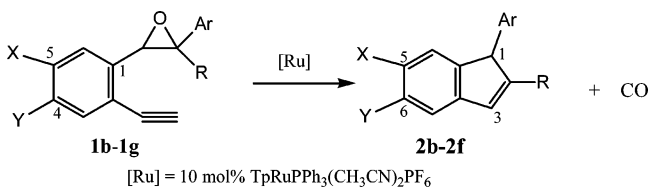reactions upon modification of the substrate frameworks and substituents.

Results and Discussion

Although 2,2-disubstituted epoxides gave 1-alkylidene-2-indanones **B**, treatment of 2-methyl-2-phenyl epoxide **1a** with TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$[10] catalyst (10 mol %) in hot toluene (100 °C, 12 h) gave 1-phenyl-2-methyl-1*H*-indene species **2a** in 78% yield. GC analysis of the gaseous mixture above the reaction solution showed the presence of carbon monoxide. High-resolution mass spectra of compound **2a** indicate loss of carbon monoxide relative to its starting epoxide **1a**. The structure is confirmed by ^{13}C NMR spectra, which shows 14 carbon peaks with one carbon less than the expectation. The proposed structure is also supported by the ^{1}H NOE effect.[11]

We prepared various 2-alkyl-2-aryl epoxides **1b**–**g** to examine the generality of this atypical cyclization. These epoxides were present as either the *E*-isomer or a mixture of *E*- and *Z*-isomers. Entries 2−4 (Table 1) show the suitability of this cyclization to the variation of alkyl and aryl substituents of epoxides with ethyl, 4-tolyl, and 4-fluorophenyl groups, and the corresponding indene products **2b**–**d** were obtained in 72−77% yields. Entries 4−6 show the cyclization of epoxides **1e**–**g** bearing a fluoro substituent at their phenyl C4 or C5 carbons respectively; the resulting indenes **2e**–**f** were obtained in 71−80% yields. The regiochemistry of indene **2e** (entry 4) was determined by ^{1}H NOE spectra.[11] Notably, the indene product generated from epoxide **1g** is identical to that given from epoxide **1e** even though these two epoxides have a fluoro substituent at different phenyl positions. This information suggests that the cyclizations of epoxide **1e** and **1g** proceed through the same intermediate.

With these encouraging results, we further examined the effects of epoxide skeletons on the cyclization chemoselectivity. We prepared various 1,2-disubstituted **3a**–**c** and 1,2,2-trisubstituted epoxides **5a**–**h** bearing a *cis*-enynyl substituent. As shown in Table 2, epoxides **3a**–**c** gave 2,5-disubstituted phenols **4a**–**c** in 45−72% yields

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(11) The ^{1}H NOE NMR spectra of key compounds **2a**, **2e**, and **6a** are shown in either the Experimental Section or the Supporting Information.

TABLE 1. Ruthenium-Catalyzed Cyclization of 2,2-Alkylaryl Epoxides

[Ru] = 10 mol% TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$

entries	epoxides[a]	indenes[b]
1	X = Y = H, Ar = Ph, R = Et (**1b**, *E*/*Z* = 1.3)	**2b** (77%)
2	X = Y = H, Ar = *p*-MePh, R = Me (**1c**, *E*/*Z* = 2.5)	**2c** (76%)
3	X = Y = H, Ar = *p*-FPh, R = Me (**1d**, *E*/*Z* = 2.6)	**2d** (72%)
4	X = H, Y = F, Ar = Ph, R = Me (**1e**, *E*-form only)	**2e** (75%)
5	X = H, Y = F, Ar = p-MePh, R = Me (**1f**, *E*-form only)	**2f** (71%)
6	X = F, Y = H, Ar = Ph, R = Me (**1g**, *E*-form only)	**2e** (80%) X = H, Y = F

[a] Conditions: [substrate] = 0.75 M, 100 °C, 12 h, toluene. [b] Yields were reported after elution from a silica column.

TABLE 2.

[Ru] = 10 mol% TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$
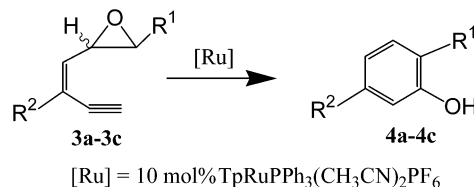
entries	epoxides[a]	phenols[b]
1	R^1 = ^{i}Pr, R^2 = nBu (**3a**)	**4a** (72%)
2	R^1 = ^{n}Bu, R^2 = ^{n}C$_6$H$_{13}$ (**3b**)	**4b** (65%)
3	R^1 = Ph, R^2 = ^{n}C$_6$H$_{13}$ (**3c**)	**4c** (45%)

[a] Conditions: [substrate] = 0.75 M, 100 °C, 12 h, toluene. [b] Yields were reported after elution from a silica column.

in the presence of ruthenium catalyst (10 mol %). The structures of phenols **4a**–**c** were confirmed by ^{1}H, ^{13}C, and high-resolution mass spectra,[11] although the outcomes of cyclization of epoxides **3a**–**c** are essentially the same as those observed for *o*-ethynylphenyl epoxides (Scheme 1) that gave 2-naphthols **A**.

As shown in Table 3, treatment of 1-*cis*-ethynyl-2,2-dialkyl epoxide **5a** (*E*/*Z* = 0.9) with ruthenium catalyst (10 mol %) afforded 6,6-disubstituted cyclohexa-2,4-dien-1-one **6a** with 90% yield. The proposed structure is compatible with its ^{1}H-NOE[11] and ^{13}C NMR spectra and by high-resolution mass spectra. This chemoselectivity is distinct from what is observed for their *o*-ethynylphenyl epoxide analogues that gave 1-alkylidene-2-indanones **B** (Scheme 1). We prepared various epoxide analogues with various *E*/*Z* ratios[12] to examine the generality of this cyclization. Entries 2−7 show the suitability of this cyclization with variation of the R^3 and R^4 substituents; the resulting cyclic ketones **6b**–**g** were obtained in 85−92% yields. We also prepared 2,2-disubstituted epoxide **5h** bearing geminal methyl and phenyl groups to examine a possible alternation of reaction selectivity like those

(12) The *E*/*Z* ratios of epoxides **3a**–**c** and **5a**–**h** are given in the Supporting Information.

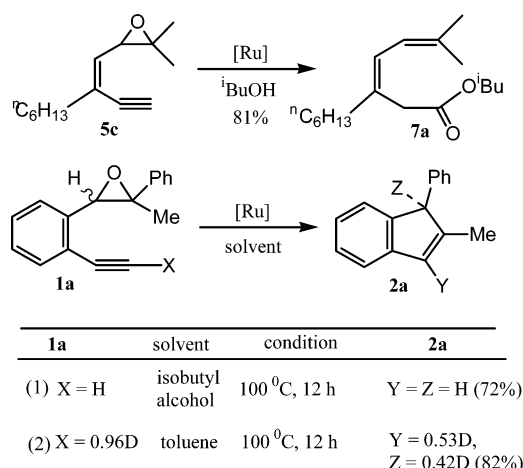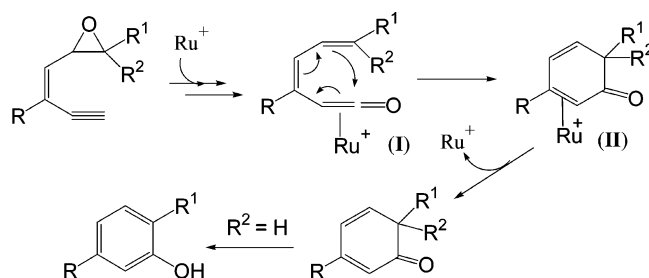## TABLE 3. Cyclization of 1-*cis*-Enynyl-2,2-dialkyl Epoxides

[Ru] = 10mol%

TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$

entries	epoxides[a]	ketones[b]
1	R^1 = ^{n}Pr, R^2 = Me R^3 = H, R^4 = Ph (5a)	6a (90%)
2	R^1 = ^{n}C$_5$H$_{11}$, R^2 = Me R^3 = H, R^4 = Ph (5b)	6b (92%)
3	R^1 = R^2 = Me R^3 = H, R^4 = ^{n}C$_6$H$_{13}$ (5c)	6c (90%)
4	R^1 = Et, R^2 = Me R^3 = H, R^4 = ^{n}C$_6$H$_{13}$ (5d)	6d (85%)
5	R^1 = R^2 = Me R^3 = H, R^4 = Ph (5e)	6e (85%)
6	R^1 = Me, R^2 = Et R^3 = H, R^4 = Ph (5f)	6f (88%)
7	R^1 = R^2 = Me R^3 = R^4 = −C$_4$H$_8$− (5g)	6g (92%)
8	R^1 = Ph, R^2 = Me R^3 = H, R^4 = ^{n}C$_6$H$_{13}$ (5h)	6h (89%)

[a] Conditions: [substrate] = 0.75 M, 100 °C, 12 h, toluene. [b] Yields were reported after elution from a silica column.

SCHEME 2

[Ru] = 10 mol% TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$
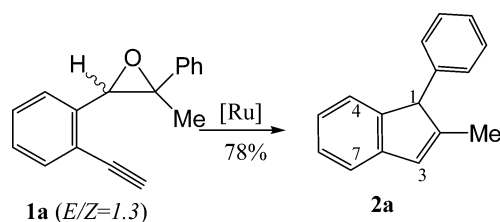
described in Scheme 2 and Table 1. Treatment of this epoxide with ruthenium catalyst in hot toluene (100 °C, 12 h) gave the same ketone **6h** in 89% yield (entry 8), and the electronic effect of the phenyl substituent of epoxide **5h** failed to alter the chemoselectivity in the way that we observed for their *o*-(ethynyl)phenyl epoxide analogues **1a**−**g**.

To examine the nature of reaction mechanism, we selected isobutyl alcohol as the reaction solvent. Epoxides **1a** and **5c** were chosen because they gave indene and cyclohexa-2,4-dien-1-one derivatives, distinct from our previous observations.[8] As shown in Scheme 3, treatment of epoxide **5c** with ruthenium catalyst (10 mol %) in hot isobutyl alcohol gave the ester **7a** in 81% yield. In contrast, the catalytic reaction of **1a** still gave indene **2a** in 72% yield. These results reveal that ruthenium−ketene intermediate (**I**) was generated for epoxide **5c** but not for compound **1a**. Notably, for the deuterated sample **1a**, its alkynyl deuterium was transferred to the C1 and C3 protons of indene **2a** with 42% and 53% deuterium contents, respectively.[13]

We propose two plausible mechanisms in Schemes 4 and 5, which account for the formation of 2,4-cyclohexadien-1-one and indene products, respectively. The mech-

SCHEME 3

| 1a	solvent	condition	2a
(1) X = H	isobutyl alcohol	100 °C, 12 h	Y = Z = H (72%)
(2) X = 0.96D	toluene	100 °C, 12 h	Y = 0.53D, Z = 0.42D (82%)

SCHEME 4

anism of formation of 2,4-cyclohexadien-1-one seems straightforward because the trapping experiment indicates that ruthenium−ketene species **I** is likely the reaction intermediate. The transformation from starting epoxide to intermediate **I** has been elucidated in our previous study.[8] As shown in Scheme 4, the 6-*endo-dig* cyclization of the terminal alkenyl carbon of species **I** at the ketene moiety[14] gave ruthenium−π-cyclohexadienone species **II** and ultimately afforded the observed cyclic ketones.

In Scheme 5, the epoxide **1a** is catalyzed by ruthenium complex to form ruthenium−vinylidenium species **III** and further to yield ruthenium−acyl species **IV** rather than the ruthenium−ketene **I** as we failed to trap species **I** with isobutyl alcohol. Species **C** equilibrates with species **V** because of the stability of a tertiary benzyl cation. This species subsequently forms ruthenium−acyl species **VI** via intramolecular attack of ruthenium at the tertiary cationic center. TpRu(IV)−acyl species **VI** is prone to decarbonylation reaction; we expect that species **VI** easily loses one CO molecule to give ruthenium−cyclohexadiene intermediate **VII** and further produces species **VIII** via reductive elimination. Addition of H$^+$ or the cationic Ru$^+$ species (M = H or Ru) to species **VIII** is expected to yield benzyl cations **IX** and **IX′**. The chemoselectivity in the

(13) The deuterium contents of 1*H*-indene **2a** were calculated by the crude products given from deutertated **1a** because purification of indene **2a** on a Et$_3$N-pretreated silica column led to a loss of deuterium content at the C1 and C3-indene proton. The C1H and C3-H deuterium contents were estimated to be 30% and 46%, respectively.

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SCHEME 5
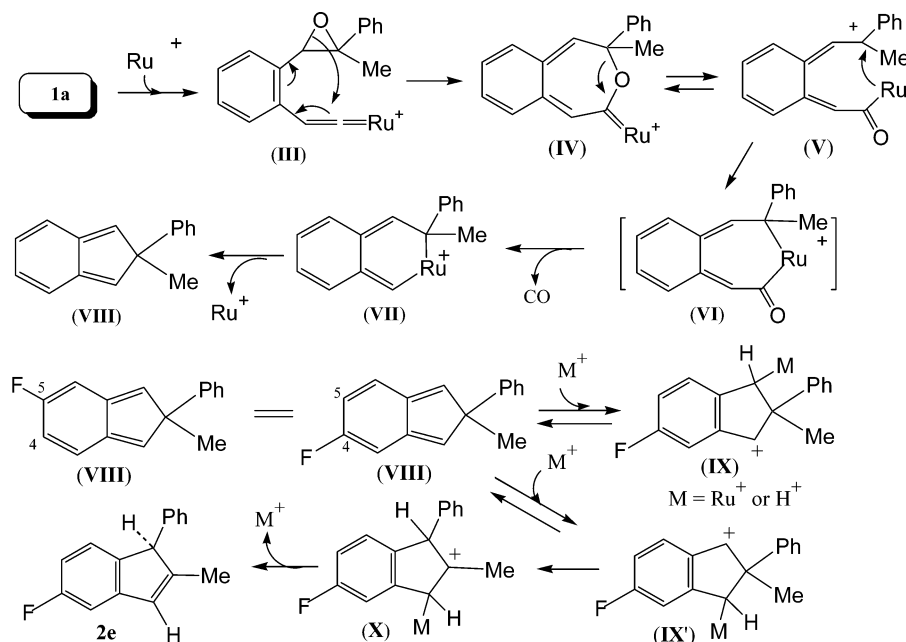
cyclization of fluorophenyl epoxides **1e** and **1g** depends on the relative stability of benzyl cations **IX** and **IX′**; a π-donor group such as fluoro prefers cation **IX′** through π-conjugation to induce 1,2-phenyl migration to give tertiary cation **X** and ultimately yields the observed product **2e**. Residual water and the acid catalyst TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$ likely generate a small amount of protons to catalyzed the conversion of species **G** to indene **2e**.

Although we obtained no direct evidence for formation of ruthenium−ketene intermediate **I**, the loss of CO indicates the formation of ruthenium(IV)−acyl intermediates.[9b] In our previous study, the TpRu(IV)−acyl species was shown to undergo decarbonylation even in the presence of alcohol or a CO atmosphere under pressure.[9b] The symmetric character of species **VIII** provides a rationale that both 5-fluoro- and 6-fluoro-substituted epoxide species **1e** and **1g** should give the same product, consistent with our observations (Table 1, entries 4 and 6). This species is also compatible with the deuterium labeling experiment in Scheme 3 that the alkynyl deuterium of **1a** was transferred equally to the at C1 and C3 protons of indene **2a**.

It is interesting to note the different chemoselectivities in the cyclization of 1-(*o*-ethynylphenyl)-2,2-dialkyl epoxides and 1-(enynyl)-2,2-disubstituted epoxides **5a−h** which gave 1-alkylidene-2-indanones **B** and 2,4-cyclohexadien-1-ones **6a−h**, respectively. This discrimination is probably due to a higher energy in the transformation of ketene species **I** to the ruthenium−dieneone **II**, which sacrifices the aromatic energy of species **I** (Scheme 6).

Conclusions. We report new patterns of the epoxide−alkyne cyclizations with alternation of the substituent and structural skeleton of the epoxide substrates. With TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$ catalyst, 1-(*o*-ethynylphenyl)-2-alkyl-2-aryl epoxides gave 1-aryl-2-alkyl-1*H*-indene derivatives and carbon monoxide in hot toluene whereas 1-*cis*-enynyl-2,2-disubstituted epoxides produced the corresponding 6,6-disubstituted cyclohexa-2,4-dien-1-ones
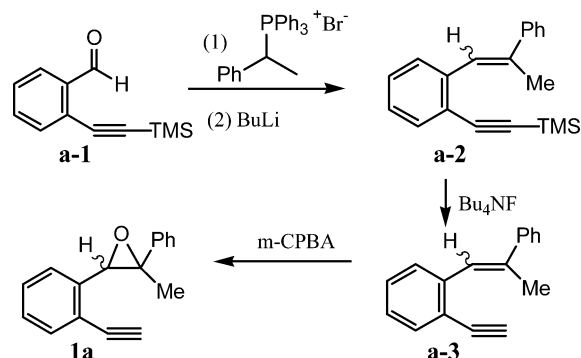
SCHEME 6
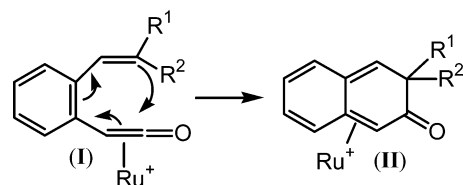
efficiently. The former is proposed to involve TpRu(IV)−acyl intermediates while the latter likely involves ruthenium−ketene species according to deuterium labeling and isobutyl alcohol trapping experiments. 6,6-Disubstituted cyclohexa-2,4-dien-1-ones are a useful building block in constructing complex molecular framework through Diels−Alder or Michael reaction.[15] This method has been applied to synthesis of naturally occurring compounds. Further application of our synthetic method for the synthesis of complex bioactive molecule is under current investigation.

Experimental Section

(1) Typical Procedure for the Synthesis of 1-(*o*-Ethynylphenyl)-2-methyl-2-phenyl Epoxides (1a). The synthetic protocol of epoxide **1a** is depicted in Scheme 7. To a THF solution (20 mL) of (α-methylbenzyl)triphenylphosphonium bromide (3.32 g, 7.42 mmol) at 0 °C was added ⁿBuLi (2.5 mL, 2.5 M, 6.43 mmol), and the mixture was stirred at 0 °C for 1.0 h. To this solution was added *o*-(2′-trimethylsilylethynyl)-benzaldehyde **a-1** (1.00 g, 4.95 mmol), and the mixture was stirred at 28 °C for 4 h. The solution was quenched with water and concentrated in vacuo. The organic layer was extracted with diethyl ether, dried over MgSO$_4$, and chromatographed (hexane, R_f = 0.75) over a silica column to give the olefination product **a-2** as a colorless oil (1.22 g, 4.20 mmol, 85%). This silyl compound was then dissolved in THF (10 mL) and added with Bu$_4$NF (1.0 M, THF, 4.65 mL, 4.60 mmol), and the mixture was stirred at 26 °C for 8 h before addition of water (10 mL). The solution was concentrated, extracted with diethyl ether, and chromatographed on a silica column (hexane, R_f =

(15) Liao, C.-C.; Peddinti, R. K. *Acc. Chem. Res.* **2002**, *35*, 856.

SCHEME 7

SCHEME 8
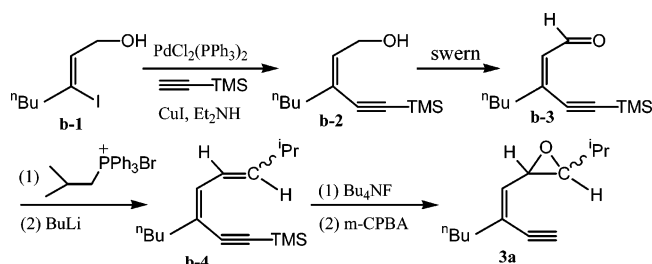
0.86) to give an enyne **a-3** (0.83 g, 3.78 mmol, 90%) as colorless oil. To a CH_2Cl_2 solution (15 mL) of this enyne (0.50 g, 2.29 mmol) was added *m*-chloroperbenzoic acid (0.52 g, 3.02 mmol), and the mixture was stirred for 3 h at 28 °C. The resulting solution was quenched with an aqueous $NaHCO_3$ solution, extracted with diethyl ether, and dried over anhydrous $MgSO_4$. The resulting solution filtered through a small basic Al_2O_3 bed, concentrated, and eluted through a Et_3N-pretreated silica column (diethyl ether–hexane, 1:1) to afford epoxide **1a** as a colorless oil (0.47 g, 2.00 mmol, 87%).

(2) Experimental Procedure for Cyclization of (*o*-Ethynyl)phenyl Epoxide (1a) to Indene 2a. A long tube containing $TpRuPPh_3(CH_3CN)_2PF_6$ (32 mg, 0.042 mmol) was dried in vacuo for 2 h before it was charged with epoxide **1a** (100 mg, 0.42 mmol) and toluene (0.56 mL). The mixture was heated at 100 °C for 12 h before cooling to room temperature. The solution was concentrated and eluted through a silica column (hexane/diethyl ether = 5/1) to afford indene **2a** (68 mg, 3.32 mmol, 78%) as a yellow oil.

(3) Typical procedure for the Synthesis of 1-*cis*-Enynyl-2-(isopropyl) Epoxide (3a). As shown in Scheme 8, to a diethylamine solution (30 mL) of *Z*-3-iodohept- 2-en-1-ol **(b-1)** (2.00 g, 8.33 mmol) were added trimethylsilylacetylene, $PdCl_2(PPh_3)_2$ (110 mg, 0.16 mmol), and CuI (15 mg, 0.80 mmol); the mixture was stirred for 28 °C for 12 h. The solution was concentrated and eluted through a silica column to afford an enynyl alcohol **b-2** as an oil (1.56 g, 7.42 mmol). To a dichloromethane solution of this alcohol (1.00 g, 4.75 mmol) were added oxalic chloride (0.50 mL, 5.9 mmol) and dimethyl sulfoxide (0.80 mL, 11.2 mmol) at −78 °C, and the mixture was stirred for 1 h before addition of Et_3N (6.6 mL, 47.6 mmol). The solution was continued to stir for 1 h before treatment with H_2O, and the organic layer was extracted with diethyl ether and chromatographed over a silica column to give aldehyde **b-3** as an oil (0.86 g, 4.14 mmol, 87%). To a THF solution (25 mL) of isobutyltriphenyl phosphonium bromide (2.30 g, 5.76 mmol) was added BuLi (2.0 mL, 2.5 M, 5.0 mmol) at 0 °C, and the mixture was stirred for 1 h before treatment with aldehyde **b-3**. The mixture was stirred for 12 h before it was added excess hexane (30 mL) to precipitate more triphenylphosphine oxide. The solution was filtered, and the filtrate was concentrated and eluted through a silica column to give the olefination product **b-4** (840 mg, 3.38 mmol, 88%) as a

colorless oil. This olefination compound was converted to the epoxide **3a** in an overall 65% yield following the same Bu_4-NF-desilylation and *m*-CPBA oxidation procedures as described in Scheme 7.

(4) Spectral Data for 1-(*o*-Ethynylphenyl)-2-methyl-2-phenyl Epoxides (1a): IR (Nujol, cm^{-1}): 3330 (s), 3100 (s), 3065 (s), 2258 (m), 2119 (s), 1625 (w), 1250 (m). ^{1}H NMR (400 MHz, $CDCl_3$): (major-*E*-isomer) δ 7.53−7.44 (m, 3 H), 7.41 (dt, $J = 8.0$, 1.0 Hz, 3 H), 7.38 (dt, $J = 7.5$, 1.0 Hz, 2 H), 7.25 (d, $J = 7.5$ Hz, 1 H), 4.20 (s, 1 H), 3.25 (s, 1 H), 1.41 (s, 3 H); (selected peaks, minor-*Z*-isomer) δ 7.43 (dt, $J = 7.5$, 1.0 Hz, 3 H), 7.18 (dt, $J = 7.5$, 1.0 Hz, 2 H), 7.13 (dt, $J = 8.0$, 1.0 Hz, 2 H), 4.45 (s, 1 H), 3.42 (s, 1 H), 1.85 (s, 3 H), the remaining peaks are overlapped with those of the major isomer. ^{13}C NMR (100 MHz, $CDCl_3$): (major *E*-isomer) δ 142.5, 139.5, 132.2, 128.6, 128.4, 127.8, 127.6, 126.7, 125.6, 121.5, 82.4, 81.8, 64.9, 64.0, 17.9. MS (75 eV, *m/z*): 234 (M$^+$). HRMS: calcd for $C_{17}H_{14}O$ 234.1045, found 234.1042.

(5) Spectral Data for 2-Methyl-1-phenyl-1*H*-indene (2a). IR (Nujol, cm^{-1}): 3030 (s), 3008 (s), 3065 (s), 2258 (m), 1625 (m), 1685 (s). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.27−7.25 (m, 3 H), 7.20 (dt, $J = 7.5$, 1.5 Hz, 2 H), 7.10 (d, $J = 8.0$ Hz, 1 H), 7.04 (d, $J = 7.5$ Hz, 1 H), 7.01(d, $J = 7.5$ Hz, 2 H), 6.53 (s, 1 H), 4.28 (s, 1 H), 1.91 (s, 3 H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.9, 148.5, 144.7, 139.7, 128.6, 128.1, 127.1, 127.0, 126.6, 124.1, 123.7, 119.7, 59.3, 15.1. HRMS: calcd for $C_{16}H_{14}$ 206.1096, found 206.1098.
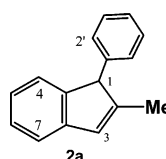
irradiation	intensity increase
H^1 (δ 4.28)	Me (δ 1.91, 1.7 %), H^4 (δ 7.25, 1.0 %)
	H$^{2'}$ (δ 7.01, 1.5 %)
H^3 (δ 6.53)	H^7 (δ 7.27, 1.0 %), Me (1.4 %)
Me (δ 1.91)	H^1 (2.8%), H^3 (4.1%)

(6) Spectral Data for 2-(2-Ethynylhex-1-enyl)-3-isopropyloxirane (3a). IR (Nujol, cm^{-1}): 2256 (m), 1620 (w), 1225 (m). ^{1}H NMR (400 MHz, $CDCl_3$): (major *trans*-isomer) δ 5.36 (d, $J = 8.7$ Hz, 1 H), 3.17 (s, 1 H), 2.77 (dd, $J = 8.6$, 4.3 Hz, 1 H), 2.63 (dd, $J = 6.8$, 1.2 Hz, 1 H), 2.13 (t, $J = 7.6$ Hz, 2 H), 1.60−1.54 (m, 1 H), 1.52−1.44 (m, 2 H), 1.32−1.25 (m, 2 H), 0.96 (d, $J = 6.8$ Hz, 3 H), 0.90 (d, $J = 6.8$ Hz, 3 H), 0.86 (t, $J = 6.5$ Hz, 3 H); (minor *cis*-isomer) δ 5.54 (d, $J = 8.7$ Hz, 1 H), 3.89 (dd, $J = 8.7$, 4.3 Hz, 1 H), 3.63 (dd, $J = 8.7$, 1.4 Hz, 1 H), 3.17 (s, 1 H), 2.16 (t, $J = 7.4$ Hz, 2 H), 1.60−1.54 (m, 1 H), 1.52−1.44 (m, 2 H), 1.32−1.25 (m, 2 H), 1.09 (d, $J = 6.7$ Hz, 3 H), 1.00 (d, $J = 6.7$ Hz, 3 H), 0.86 (t, $J = 6.5$ Hz, 3 H). ^{13}C NMR (150 MHz, $CDCl_3$): (major *trans*-isomer) δ 135.6, 128.8, 82.9, 81.2, 65.4, 55.5, 36.9, 36.6, 30.5, 30.0, 21.9, 20.2, 18.3; (minor *cis*-isomer) δ 132.6, 127.6, 82.5, 81.1, 64.8, 55.4, 36.9, 36.6, 30.0, 28.1, 21.8, 18.9, 13.8. MS (75 eV, *m/z*): 192 (M$^+$). HRMS: calcd for $C_{13}H_{20}O$ 192.1514, found 192.1520.

(7) Spectral Data for 5-Butyl-2-isopropyl-phenol (4a). IR (Nujol, cm^{-1}): 3610 (s), 1580 (m), 1625 (w), 1225 (m). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.08 (d, $J = 8.0$ Hz, 1 H), 6.73 (d, $J = 8.0$ Hz, 1 H), 6.57 (s, 1 H), 4.84 (bs, OH), 3.19−3.12 (m, 1 H), 2.51 (t, $J = 7.6$ Hz, 2 H), 1.58−1.53 (m, 2 H), 1.37−1.32 (m, 2 H), 1.24 (s, 3 H), 1.23 (s, 3 H), 0.91 (t, $J = 7.4$ Hz, 3 H). ^{13}C NMR (150 MHz,$CDCl_3$): δ 152.5, 141.6, 131.4, 126.1, 120.9, 115.2, 35.0, 33.4, 26.7, 22.7, 22.6, 22.3, 13.9. HRMS: for $C_{13}H_{20}O$ calcd 192.1514, found 192.1518.

Supporting Information Available: Spectral data of compounds **1a−g**, **2b−f**, **3b**,**c**, **4b**,**c**, **5a−h**, **6a−h**, and **7a** in repetitive experiments; ^{1}H and ^{13}C NMR spectra of key compounds. This material is available free of charge via the Internet at http://pubs.acs.org.