Novel Synthesis of Nitrogen Heterocycles Using Zirconium-Promoted Reductive Cyclization

Miwako Mori,*,† Noriaki Uesaka,† Fumihiko Saitoh,† and Masakatsu Shibasaki‡

Faculty of Pharmaceutical Sciences, Hokkaido University, Sapporo 060, Japan, and Faculty of Pharmaceutical Sciences, University of Tokyo, Hongo, Bunkyou-ku, Tokyo 113, Japan

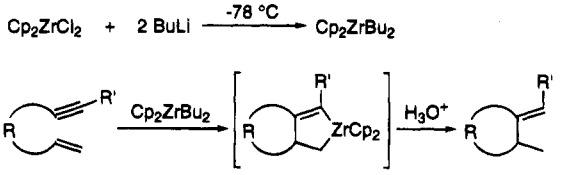
Received February 17, 1994®

Perhydroindole derivatives were prepared from enynes using zirconium-promoted reductive cyclization. The zirconacycles derived from enynes **1** were treated with iodine, isonitriles, oxygen, and carbon monoxide to give various heterocycles. The carbon–zirconium bonds of the zirconacycle could be selectively cleaved by different reagents.

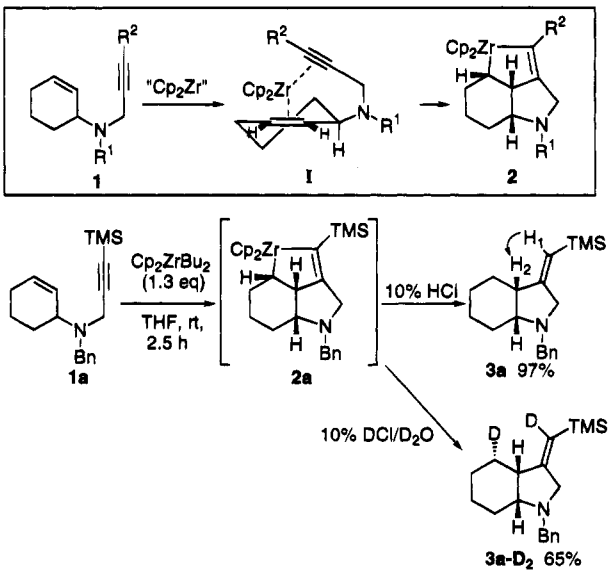
Introduction

Carbon–carbon bond formation from multiple bonds using transition metals such as Pd, Co, Rh, and Zr is a powerful synthetic method.[1–4] In particular, cyclizations of enynes, dienes, and diynes are very important processes in current organic chemistry. In these reactions, metallacycles are formed as intermediates. With late transition metals, reductive elimination or β-hydride elimination from these metallacycles occurs to give low-valent metal complexes, and catalytic cycles can be established. However, metallacycles derived from early transition metals such as Ti or Zr are fairly stable. Thus, highly regio- and stereocontrolled products can be obtained by treatment of these metallacycles with reagents such as protons, halogens, isonitriles, carbon monoxide, and oxygen. Negishi *et al.* reported a useful synthesis of Cp_2ZrBu_2 from Cp_2ZrCl_2 and BuLi.[2b] Negishi[2] and Nugent[3] independently reported cyclizations of enynes, dienes, and diynes using Cp_2ZrBu_2 prepared from Cp_2ZrCl_2 and BuLi (Scheme 1). It was expected that this method would be useful for the synthesis of heterocycles.

Scheme 1



Scheme 2



New we want to report a new synthesis of heterocycles using zirconium-promoted reductive cyclization.[5]

Reaction of Enyne 1a with Dibutylzirconocene

It was expected that treatment of cyclohexenylamines **1** having an alkyne moiety on nitrogen with zirconocene would give the zirconacycle **2** *via* I with regio- and stereocontrol. When a THF solution of cyclohexenylamine **1a** (1 equiv) and dibutylzirconocene (1.3 equiv), prepared from Cp_2ZrCl_2 and BuLi,[2b] was stirred at room temperature for 2.5 h and the resultant zirconacycle was hydrolyzed with 10% HCl, perhydroindole derivative **3a** was obtained as a single isomer in 97% yield (Scheme 2). The NOE observed between protons H_1 and H_2 of **3a** indicated that the *Z*-olefin was formed selectively. The intermediary zirconacycle was treated with 10% DCl–D_2O to afford deuterated compound **3a-D$_2$**. The NMR

† Hokkaido University.
‡ University of Tokyo.
® Abstract published in *Advance ACS Abstracts,* September 1, 1994.

(1) Pd: Trost, B. M.; Lautens, M. *J. Am. Chem. Soc.* **1985**, *107*, 1781. Trost, B. M.; Chen, S.-F. *J. Am. Chem. Soc.* **1986**, *108*, 6053. Co: Khand, I. U.; Knox, G. R.; Pauson, P. L.; Watts, W. E.; Foreman, M. *J. Chem. Soc., Perkin Trans. 1* **1973**, 977. Rh: Grigg, R.; Mitchell, T. R. B.; Ramasubbu, A. *J. Chem. Soc., Chem. Commun.* **1980**, 27.

(2) (a) Negishi, E.-i.; Holmes, S. J.; Tour, J. M.; Miller, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 2568. (b) Negishi, E.-i.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (c) Negishi, E.-i.; Swanson, D. R.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1987**, *28*, 917. (d) Negishi, E.-i.; Swanson, D. R.; Miller, S. R. *Tetrahedron Lett.* **1988**, *29*, 1631. (e) Negishi, E.-i.; Takahashi, T. *Synthesis* **1988**, 1. (f) Negishi, E.-i.; Miller, S. R. *J. Org. Chem.* **1989**, *54*, 6014. (g) Negishi, E.-i.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336. (h) Swanson, D. R.; Rousset, C. J.; Negishi, E.-i. *J. Org. Chem.* **1989**, *54*, 3521. (i) Swanson, D. R.; Negishi, E.-i. *Organometallics* **1991**, *10*, 825.

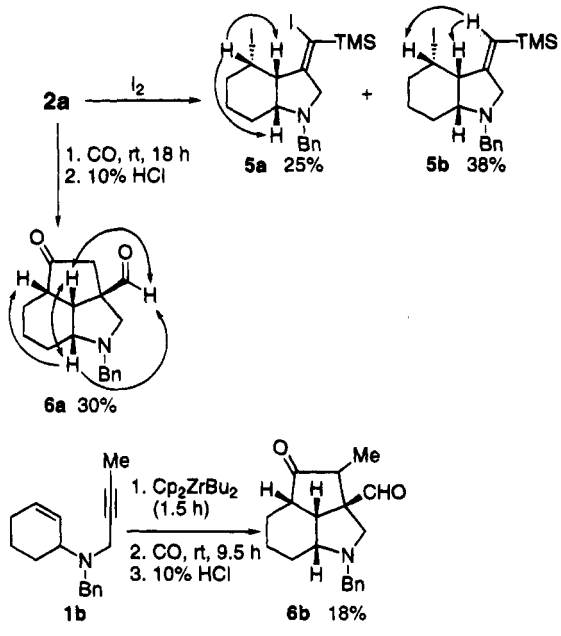
(3) Nugent, W. A.; Calabrese, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 6422. Nugent, W. A.; Thron, D. L.; Harlow, R. H. *J. Am. Chem. Soc.* **1987**, *109*, 2788. Rajanbabu, T. V.; Nugent, W. A.; Taber, D. F.; Fagan, P. J. *J. Am. Chem. Soc.* **1988**, *110*, 7128. Nugent, W. A.; Taber, D. F. *J. Am. Chem. Soc.* **1989**, *111*, 6435.

(4) (a) Bauchwald, S. L.; Watson, B. T. *J. Am. Chem. Soc.* **1987**, *109*, 2544. Buchwald, S. L.; LaMaire, S. J. *Tetrahedron Lett.* **1987**, *28*, 295. Buchwald, S. L.; Nielsen, R. B. *Chem. Rev.* **1988**, *88*, 1047. Buchwald, S. L.; Watson, B. T.; Wannamaker, M. W.; Dewan, J. C. *J. Am. Chem. Soc.* **1989**, *111*, 4486. Buchwald, S. L.; Kreutzer, K. A.; Fisher, R. A. *J. Am. Chem. Soc.* **1990**, *112*, 4600. Buchwald, S. L.; King, S. M. *J. Am. Chem. Soc.* **1991**, *113*, 258. Tidwell, J. H.; Senn, D. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **1991**, *113*, 4685. Barr, K. J.; Watson, B. T.; Buchwald, S. L. *Tetrahedron Lett.* **1991**, *32*, 5465. (b) Jensenn, M.; Livinghouse, T. *J. Am. Chem. Soc.* **1989**, *111*, 4495. Van Wagenen, B. C.; Livinghouse, T. *Tetrahedron Lett.* **1989**, *30*, 3495. (c) Coles, N.; Whitby, R. J.; Blagg, J. *Synlett.* **1990**, 271.

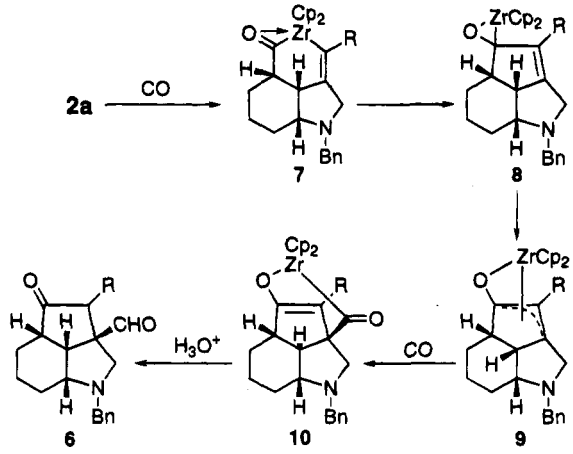
(5) Mori, M.; Uesaka, N.; Shibasaki, M. *J. Chem. Soc., Chem. Commun.* **1990**, 1222. Mori, M.; Uesaka, N.; Shibasaki, M. *J. Org. Chem.* **1992**, *57*, 3519.

0022-3263/94/1959-5643$04.50/0

Scheme 3



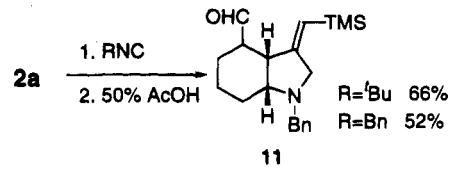
Possible Reaction Course



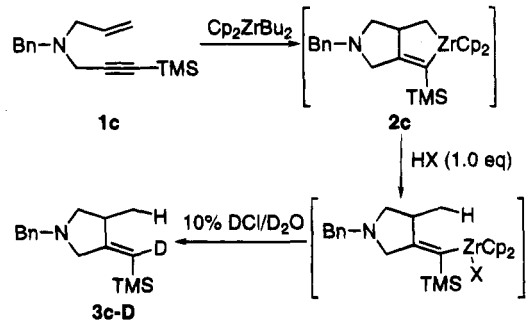
spectrum indicated that deuteriums were incorporated at the vinylic position and on the cyclohexyl moiety.

Zirconacycle **2a** was treated with iodine to give two iodinated products **5a** and **5b** in 25% and 38% yields, respectively (Scheme 3). The mass spectra of these products indicated that two iodines had been introduced in the former compound and that the latter product had one iodine. NOE experiments on these compounds suggested that the ring junction of the cyclized product was *cis* and that the iodo group on the cyclohexyl moiety of **5a** was *trans* to the ring junction protons, that is, that the structure of the zirconacycle was **2a**. The results indicate that highly regio- and stereocontrolled products are obtained from **2a** by this one-pot reaction. When the argon atmosphere in the reaction vessel of zirconacycle **2a** was exchanged for carbon monoxide and the solution was stirred at room temperature overnight, a carbonylated product whose IR spectrum exhibited the presence of two carbonyl groups (1740 and 1720 cm^{-1}) was obtained. From the spectral data, the structure of this compound was confirmed as **6a**. An NOE experiment on compound **6a** indicated that the ring junction protons and the aldehyde proton were *cis*. Similar treatment of enyne **1b** with Cp_2ZrBu_2 followed by treatment with carbon monoxide afforded compound **6b** as a single isomer, but

Scheme 4



Scheme 5



the yield was low. Though the reason why two carbonyl groups were incorporated into these compounds is not clear, the reaction mechanism is believed to be the following. Presumably, the insertion of carbon monoxide into zirconacycle **2a** gives acylzirconacycle **7**, which would easily convert into oxazirconacycle **8**. Then, complex **8** would convert to (π-allyl)zirconium complex **9**. The insertion of carbon monoxide into **9** would afford **10**, and subsequent acid treatment would give compound **6**.[6]

The insertion of isonitrile into the carbon–zirconium bond was also examined. When zirconacycle **2a** was treated with *t*-BuNC and then with 50% AcOH, aldehyde **11** was obtained in 66% yield as a single isomer (Scheme 4). Similar treatment of compound **2a** with $PhCH_2NC$ afforded compound **11** in 52% yield. Though the stereochemistry of the aldehyde group could not be determined, it was expected to be *trans* to the ring junction protons.

Selective Cleavage of the Carbon–Zirconium Bonds of the Zirconacycle

A selective cleavage of the carbon–zirconium bond of zirconacycle **2** could be realized because of the difference in the reactivity between the sp^3 carbon–zirconium bond and the sp^2 carbon–zirconium bond. In order to examine the difference between these reactivities, the zirconacycle was treated with acetic acid and then with 10% DCl. Zirconacycle **2c**, prepared from enyne **1c** and Cp_2ZrBu_2 (1.3 equiv) in THF, was treated at 0 °C with acetic acid (1.0 equiv), and subsequent treatment with 10% DCl–D_2O gave monodeuterated product **3c-D** in 96% yield (Scheme 5). The D content was calculated from the ratio of the integrations of the vinylic proton (s, δ, 5.30) and the C_4 proton (m, δ 2.6) of the pyrrolidine ring (see Figure 2). From the NMR spectrum, the D content was calculated as 33% (Table 1, run 1). The sp^3 carbon–zirconium bond could not be cleaved selectively (run 2) even at the lower temperature. Thus, TFA was used instead of acetic acid. The lower reaction temperature improved the selectivity of the cleavage of carbon–zirconium bonds (run 4). When zirconacycle **2c** was treated first with TFA at −78 °C for 5 h and then with 10% DCl–D_2O, monodeuterated product **3c-D** was obtained in quantitative yield (D content 82%, Table 1, run 7). The NMR spectra

(6) Desilation of β-silyl ketone would occur by acid treatment. Cf. Brook, A. G. *Acc. Chem. Res.*, **1974**, *7*, 77.

Table 1. Selective Cleavage of 3 under Various Conditions

run	HX	temp (°C)	time (h)	yield (%)	D content[a] (%)
1	AcOH	0	1	96	33
2	AcOH	−30	3	79	68
3	TFA	−30	1	99	35
4	TFA	−30	3	89	70
5	TFA	−50	3	93	77
6	TFA	−78	3	80	82
7	TFA	−78	5	quant	82

[a] D content of the vinylic proton H_b. D content was calculated from the ratio of H_b to H_a on the NMR spectrum.

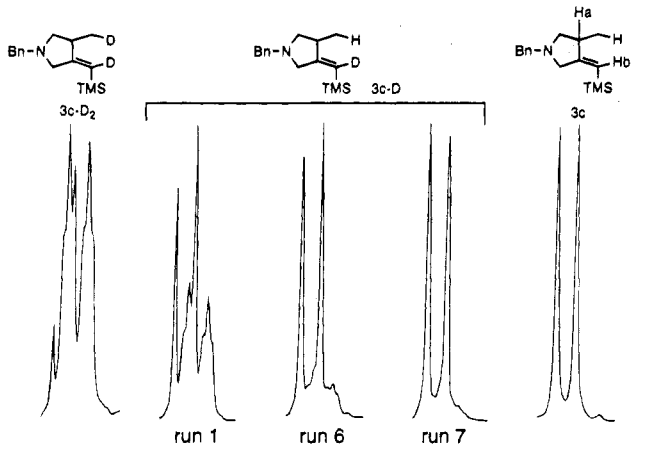


Figure 1. NMR spectra of the methyl group on the pyrrolidine ring of 3c-D.

of the methyl protons on the pyrrolidine ring of deuterated product **3c-D** are shown in Figure 1. The methyl group of **3c-D** appeared as a clear doublet in the case of run 7 (Figure 1, run 7).

On the one hand, when zirconacycle **2a** was treated at 0 °C with an equimolar amount of propionic acid and then with 10% DCl−D_2O, monodeuterated product **3a**-D was obtained in 45% yield (D content, 96%) (Scheme 6). On the other hand, when treated with *t*-BuNC and then with iodine, **2a** gave compound **12** in 42% yield. These results suggest that the sp^3 carbon−zirconium bond of zirconacycle **2** is more reactive than the sp^2 carbon−zirconium bond.

Synthesis of the Azatricyclo[7.3.0.0^{4,8}]dodecene Skeleton

This procedure was further extended to the synthesis of other heterocycles (Scheme 7). Starting enyne **1d** was prepared from amino alcohol **13**.[7] Jones oxidation of compound **13** followed by treatment of the resulting ketone with propargyl bromide gave keto alkyne **14** in 73% yield. A Wittig reaction of **14** afforded the enyne in 93% yield. The terminal alkyne was protected with a TMS group to give **1d** in 97% yield. A THF solution of compound **1d** was stirred with Cp_2ZrBu_2 (1.3 equiv) at room temperature for 3 h, and subsequent treatment with 10% HCl gave perhydroindole derivative **3d** in 87% yield as the sole product. This result means that the disubstituted alkene can react with zirconocene to form a zirconacycle. An NOE experiment on compound **3d** shows that the ring junction is *cis* and that the Z-isomer is formed. These results mean that the stereochemistry of the zirconacycle is that of **2d**. The argon atmosphere

(7) Mori, M.; Saitoh, F.; Uesaka, N.; Okamura, K.; Date, T. *J. Org. Chem.* **1994**, in press. Smith, J. G. *Synthesis* **1984**, 629. Posnar, G. H.; Rogers, D. Z. *J. Am. Chem. Soc.* **1977**, *99*, 8208.

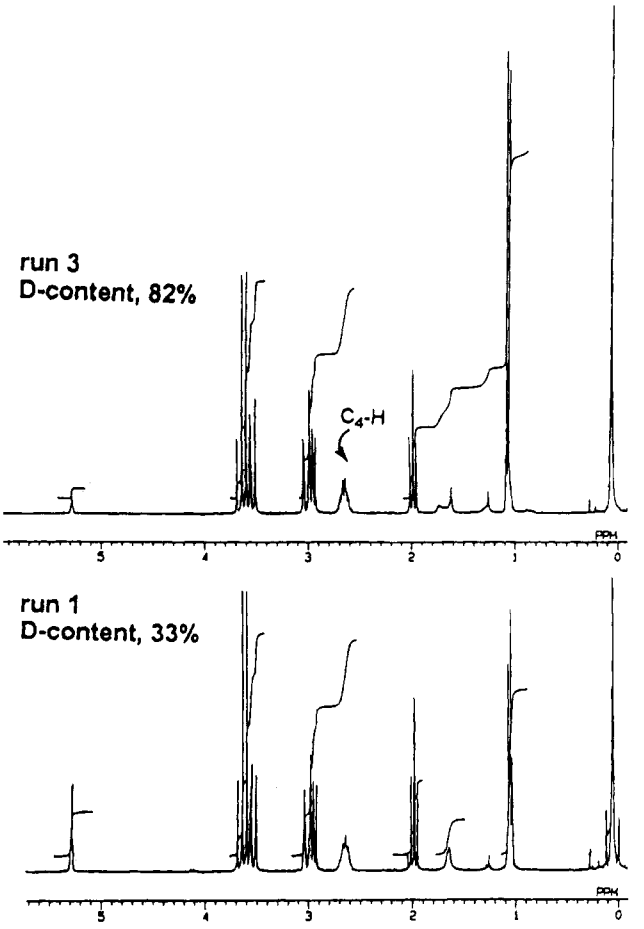
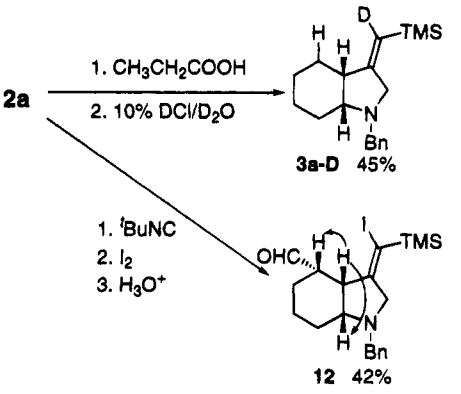


Figure 2.

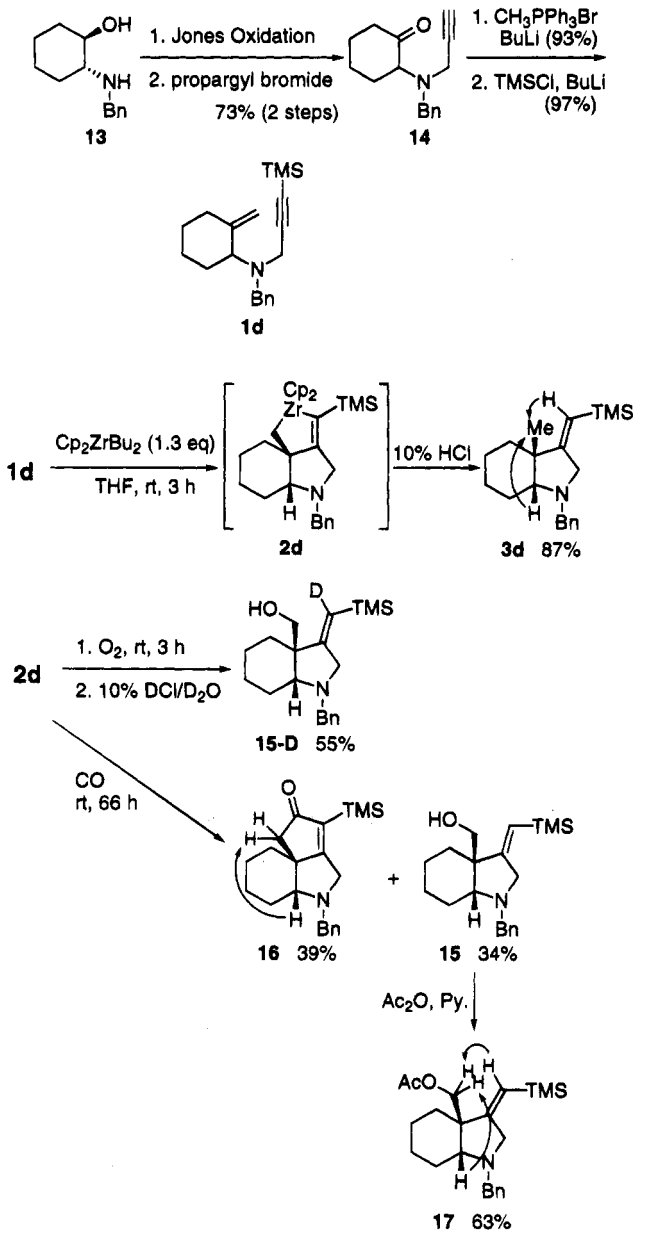
Scheme 6



of the reaction vessel containing the zirconacycle was exchanged for oxygen, and the solution was stirred for 3 h. After treatment of the reaction mixture with 10% DCl−D_2O, alcohol **15-D** was obtained in 55% yield. The result indicates that the hydroxy group was introduced at the sp^3 carbon−zirconium bond of **2d** and deuterium was introduced at the sp^2 carbon−zirconium bond. In this case, the completely selective cleavage of carbon−zirconium bonds was also achieved. Subsequently, the insertion of carbon monoxide into zirconacycle **2d** was carried out, and tricyclic ketone **16** was obtained in 39% yield along with alcohol **15** (34% yield). Compound **15** could be obtained from oxygen in the reaction vessel, and the structure was confirmed by conversion of **15** into acetate **17**.

Zirconium-promoted reductive coupling is a quite interesting and useful method for the synthesis of heterocycles. Highly regio- and stereocontrolled products

Scheme 7



were obtained by a one-pot reaction of the starting enyne. Thus, numerous heterocycles could be synthesized using this procedure.

Experimental Section

All manipulations were performed under an argon atmosphere. Solvents were distilled under an argon atmosphere from sodium benzophenone (THF) or CaH_2 (CH_2Cl_2). All other reagents and solvents were purified when necessary using standard procedures. Column chromatography was performed on silica gel 60 (70–230 mesh, 60 Å), and flash chromatography was performed on silica gel 60 (230–400 mesh, 60 Å) using the indicated solvent. Melting points are uncorrected.

***N*-Benzyl-*N*-(2-cyclohexen-1-yl)(3-(trimethylsilyl)-2-propynyl)amine (1a). (i) *N*-Benzyl-*N*-(2-cyclohexen-1-yl)-2-propynylamine (Propargylamine, Precursor of 1a).** To a stirred suspension of *N*-benzyl-2-cyclohexenylamine (502.7 mg, 2.67 mmol) in acetonitrile (25 mL) at 0 °C containing K_2CO_3 (749.1 mg, 5.34 mmol) was added propargyl bromide (0.36 mL, 4.01 mmol). After the mixture was stirred at rt for 28 h, H_2O (2.0 mL) was added to the suspension. The aqueous layer was extracted with AcOEt, and the combined organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:40) to afford 574.7 mg (96%) of propargylamine as a colorless oil: IR (neat) 3300, 1645, 1600 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.12–2.12 (m, 6 H), 2.20 (t, J = 2.5 Hz, 1 H), 3.34 (d, J = 2.5 Hz, 2H), 3.40–3.64 (m, 1 H), 3.64 (d, J = 13.8 Hz, 1 H), 3.88 (d, J = 13.8 Hz, 1 H), 5.66–6.00 (m, 2H), 6.10–6.48 (m, 5H); MS (EI, *m/z*) 225 (M^+, 4), 197 (33), 134 (4), 106 (25), 91 (100), 81; HRMS (EI, *m/z*) for $C_{16}H_{19}N$, calcd 225.1517, found 225.1509.

(ii) 1a. To a stirred solution of propargylamine (400.0 mg, 1.8 mmol) in THF (5.0 mL) at −78 °C was added BuLi (1.6 M solution in hexane, 1.35 mL, 2.2 mmol). After the solution was stirred at −78 °C for 40 min, trimethylsilyl chloride (0.43 mL, 2.7 mmol) was added at −78 °C, and the solution was allowed to warm to rt. After the mixture was stirred at rt for an additional 5 h, H_2O (2.0 mL) was added to the solution. The resultant mixture was extracted with AcOEt, and the organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:10) to afford 437.2 mg (83%) of **1a** as a colorless oil: IR (neat) ν 1645, 1600 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.18 (s, 9 H), 1.36–2.18 (m, 6H), 3.24–3.62 (m, 1 H), 3.36 (s, 2 H), 3.64 (d, J = 13.4 Hz, 1 H), 3.86 (d, J = 13.4 Hz, 1 H), 5.82 (br s, 2 H), 7.08–7.48 (m, 5 H); MS (EI, *m/z*) 297 (M^+, 11), 282 (4), 269 (50), 254 (21), 243 (7), 224 (2), 216 (3), 206 (8), 196 (29), 186 (13), 178 (38), 158 (21), 91 (100), 73; HRMS (EI, *m/z*) for $C_{19}H_{27}NSi$, calcd 297.1912, found 297.1886. Anal. Calcd for $C_{19}H_{27}NSi$: C, 76.71; H, 9.15; N, 4.71. Found: C, 76.60; H, 9.16; N, 4.70.

***N*-Benzyl-*N*-(2-cyclohexen-1-yl)-2-butynylamine (1b).** To a 0 °C stirred suspension of *N*-benzyl-2-cyclohexenylamine (104.5 mg, 0.56 mmol) in acetonitrile (1.2 mL) containing K_2CO_3 (749.1 mg, 5.34 mmol) and sodium iodide (101.8 mg, 0.67 mmol) was added 2-butynyl methanesulfonate (99.8 mg, 0.67 mmol). After the mixture was stirred at rt for 4.5 h, H_2O (1.0 mL) was added to the suspension, and the resultant mixture was extracted with AcOEt. The combined organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:30) to afford 116.2 mg (87%) of **1b** as a colorless oil: IR (neat) ν 1648, 1602 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 1.28–2.14 (m, 6 H), 1.82 (t, J = 2.3 Hz, 3 H), 3.27 (q, J = 2.3 Hz, 2 H), 3.36–3.70 (m, 1 H), 3.56 (d, J = 13.7 Hz, 1 H), 3.82 (d, J = 13.7 Hz, 1 H), 5.73–5.90 (m, 2 H), 7.04–7.48 (m, 5 H); MS (EI, *m/z*) 239 (M^+, 21), 211 (55), 196 (14), 186 (10), 185 (15), 158 (15), 148 (10), 91 (100); HRMS (EI, *m/z*) for $C_{17}H_{21}N$, calcd 239.1674, found 239.1663. Anal. Calcd for $C_{17}H_{21}N$; C, 85.31; H, 8.84; N, 5.85. Found: C, 85.26; H, 8.95; N, 5.85.

2-(*N*-Benzyl-*N*-propargylamino)cyclohexanone (14). To a stirred solution of *trans*-2-(*N*-benzylamino)cyclohexanol (51.1 mg, 0.25 mmol) in acetone (2.0 mL) at 0 °C was added Jones reagent (8.0 N, 4.0 mL). After the solution was stirred at rt for 18.5 h, it was cooled to 0 °C. ^{i}PrOH (1.0 mL) was added, and the solution was stirred at rt for 10 min. After the mixture was filtered through Celite, the solvent was removed. To a 0 °C solution of the residue in CH_3CN (2.0 mL) containing K_2CO_3 (69.1 mg, 0.50 mmol) was added propargyl bromide (0.033 mL, 0.37 mmol). After the mixture was stirred at rt for 28 h, saturated $NaHCO_3$ (1.0 mL) was added, and the resultant mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (AcOEt–hexane, 1:4) to afford 44.0 mg (73%, 2 steps) of **14** as a colorless oil: IR (neat) ν 3289, 2105, 1715 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.40–2.44 (m, 8 H), 2.18 (t, J = 2.7 Hz, 1 H), 2.60 (m, 1 H), 3.36 (d, J = 7.0 Hz, 1 H), 3.40 (d, J = 7.0 Hz, 1H), 3.64 (d, J = 14.0 Hz, 1 H), 3.70 (d, J = 14.0 Hz, 1 H), 7.20–7.40 (m, 5 H); MS (EI, *m/z*) 241 (M^+, 3), 213 (15), 184 (11), 170 (20), 150 (19), 144 (10), 122 (19), 91 (100); HRMS (EI, *m/z*) for $C_{16}H_{19}NO$, calcd 241.1467, found 241.1479. Anal. Calcd for $C_{16}H_{19}INO$: C, 79.63; H, 7.94; N, 5.80. Found: C, 79.72; H, 8.05; N, 5.70.

1-(*N*-Benzyl–(3-(trimethylsilyl)-2-propynyl)amino)-2-methylenecyclohexane (1d). (i) 1-(*N*-Benzyl-*N*-propargylamino)-2-methylenecyclohexane. To a stirred solution of PPh_3MeBr4 (193.0 mg, 0.54 mmol) in THF (1.0 mL) at −78 °C was added BuLi (1.60 M solution in hexane, 0.28 mL, 0.45

mmol). After the solution was stirred at 0 °C for 40 min, it was cooled to −78 °C. A solution of **14** (44.0 mg, 0.18 mmol) in THF (1.0 mL) was added, and the solution was stirred at rt for 3.5 h. To the solution was added saturated $NaHCO_3$ (1.0 mL), and the resultant mixture was extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt−hexane, 1:8) to afford 39.9 mg (93%) of propargylamine as a colorless oil: IR (neat) ν 3304, 2105, 1651 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 0.70−2.60 (m, 9 H), 2.14 (t, J = 2.6 Hz, 1 H), 3.24 (m, 2 H), 3.55 (d, J = 13.2 Hz, 1 H), 3.70 (d, J = 13.2 Hz, 1 H), 4.78 (m, 1 H), 4.90 (m, 1 H), 7.20−7.40 (m, 5 H); MS (EI, m/z) 239 (M^+, 13), 238 (13), 211 (26), 184 (21), 170 (8), 144 (8), 104 (6), 91 (100), 77 (11); HRMS (EI, m/z) for $C_{17}H_{21}N$, calcd 239.1674, found 239.1671. Anal. Calcd for $C_{17}H_{21}N$: C, 85.31; H, 8.84; N, 5.85. Found: C, 85.46; H, 9.08; N, 5.68.

(ii) 1d. To a stirred solution of propargylamine (479.0 mg, 2.00 mmol) in THF (10 mL) at −78 °C was added BuLi (1.63 M solution in hexane, 1.47 mL, 2.40 mmol). After the solution was stirred at −78 °C for 40 min, trimethylsilyl chloride (0.38 mL, 3.00 mmol) was added to the solution at −78 °C, and the solution was allowed to warm to rt. After the solution was stirred at rt for an additional 12 h, H_2O (2.0 mL) was added. The resultant mixture was extracted with AcOEt, and the organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt−hexane, 1:30) to afford 604.0 mg (97%) of **1d** as a colorless oil: IR (neat) ν 1651, 1250, cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.17 (s, 9 H), 1.38−1.58 (m, 3 H), 1.73−1.79 (m, 2 H), 2.00−2.08 (m, 2 H), 2.33−2.42 (m, 1 H), 3.15 (d, J = 3.7 Hz, 1 H), 3.16 (d, J = 17.8 Hz, 1 H), 3.27 (d, J = 17.8 Hz, 1 H), 3.54 (d, J = 13.6 Hz, 1 H), 3.65 (d, J = 13.6 Hz, 1 H), 4.76 (dd, J = 1.5, 2.2 Hz, 1 H), 4.88 (d, J = 2.2 Hz, 1 H), 7.16−7.33 (m, 5 H); MS (EI, m/z) 311 (M^+, 13), 296 (7), 256 (24), 238 (19), 216 (10), 166 (36), 95, 91 (100), 73; HRMS (EI, m/z) for $C_{20}H_{29}NSi$, calcd 311.2070, found 311.2076. Anal. Calcd for $C_{20}H_{29}NSi$: C, 77.10; H, 9.38; N, 4.50. Found: C, 77.21; H, 9.43; N, 4.53.

General Procedure for Preparing Zirconacycles. By means of Negishi's procedure, BuLi (1.60 M solution in hexane, 0.31 mL, 0.5 mmol) was added dropwise to a stirred suspension of Cp_2ZrCl_2 (0.26 mmol) in THF (0.5 mL) at −78 °C. After the mixture was stirred at −78 °C for 1 h, enyne (0.2 mmol) in THF (1.0 mL) was added. The solution was allowed to warm to rt and stirred for 2.5 h to give the zirconacycle.

(3a*R,7a*R**)-1-Benzyl-3-((*Z*)-(trimethylsilyl)methylene)-perhydroindole (3a).** To a 0 °C stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (64.2 mg, 0.22 mmol), BuLi (1.62 M solution in hexane, 0.27 mL, 0.43 mmol), and **1a** (49.8 mg, 0.17 mmol) in THF (1.5 mL)] was added 10% HCl (1.0 mL). After the solution was stirred ar rt for 1 h, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt−hexane, 1:60) to afford 49.5 mg (97%) of **3a** as a colorless oil: IR (neat) ν 1634, 1246 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.03 (s, 9 H), 1.10−1.85 (m, 8 H), 2.46−2.53 (m, 1 H), 2.73−2.78 (m, 1 H), 3.07 (dd, J = 2.2, 15.0 Hz, 1 H), 3.51 (d, J = 13.6 Hz, 1H), 3.66 (d, J = 15.0 Hz, 1 H), 3.95 (d, J = 13.6 Hz, 1 H), 5.25 (dd, J = 2.2, 4.4 Hz, 1 H), 7.22−7.39 (m, 5 H); MS (EI, m/z) 299 (M^+, 13), 284 (4), 266 (25), 208 (10), 91 (100), 73; HRMS (EI, m/z) for $C_{19}H_{29}NSi$, calcd 299.2070, found 299.2076. Anal. Calcd for $C_{19}H_{29}NSi$: C, 76.19; H, 9.76; N, 4.68. Found: C, 76.08; H, 9.86; N, 4.75.

(3a*R,4*S**,7a*R**)-1-Benzyl-4-deuterio-3-((*Z*)-deuterio-(trimethylsilyl)methylene)perhydroindole (3a-D_2).** To a 0 °C stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (179.0 mg, 0.61 mmol), BuLi (1.60 M solution in hexane, 0.70 mL, 1.13 mmol), and **1a** (49.3 mg, 0.17 mmol) in THF (1.5 mL)] was added 10% (DCl/D_2O) (1.0 mL). After the solution was stirred at rt for 1 h, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt−hexane, 1:60) to afford 33.1 mg (65%) of **3a-D_2** as a colorless oil: IR (neat) ν 1630 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.02 (s, 9 H), 1.00−2.12 (m, 7 H), 2.52 (dd, J = 4.3, 5.2 Hz, 1 H), 2.78 (m, 1 H), 3.05 (d, J = 15.0 Hz, 1 H), 3.34 (d, J = 13.5 Hz, 1 H), 3.51 (dd, J = 1.5, 15.0 Hz, 1 H), 3.95 (d, J = 13.5 Hz, 1 H), 7.15−7.40 (m, 5 H); MS (EI, m/z) 301 (M^+, 15), 258 (6), 228 (23), 210 (6), 91 (100), 73; HRMS (EI, m/z) for $C_{19}H_{27}ND_2Si$, calcd 301.2195, found 301.2173.

(3a*R,4*S**,7a*R**)-1-Benzyl-4-iodo-3-((*Z*)-iodo(trimethylsilyl)methylene)perhydroindole (5a) and (3a*R**,4*S**,7a*R**)-1-Benzyl-4-iodo-3-((*Z*)-(trimethylsilyl)methylene)-perhydroindole (5b).** To a −78 °C stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (128.9 mg, 0.44 mmol), BuLi (1.62 M solution in hexane, 0.52 mL, 0.85 mmol), and **1a** (99.5 mg, 0.34 mmol) in THF (3.0 mL)] was added I_2 (262.9 mg, 1.02 mmol) in THF (4.0 mL), and the solution was stirred at −78 °C for 30 min and at rt for 3.5 h. To the solution at −0 °C was added 20% $Na_2S_2O_3$ (2.0 mL), and the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by flash column chromatography (AcOEt−hexane, 1:60) to afford 47.3 mg (25%) of **5a** and 55.4 mg (38%) of **5b** as colorless oils: **5a**: IR (neat) ν 1604, 1248, 1198 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.08 (s, 9 H), 1.25−2.28 (m, 5H), 2.42−2.59 (m, 1H), 2.87−2.99 (m, 1H), 2.94 (d, J = 14.7 Hz, 1H), 3.12 (d, J = 13.2 Hz, 1H), 3.31 (dd, J = 4.4, 9.2 Hz, 1H), 3.68 (d, J = 14.7 Hz, 1H), 3.99 (d, J = 13.2 Hz, 1H), 4.61 (ddd, J = 3.7, 9.2 Hz, 11.0 Hz, 1H), 7.12−7.38 (m, 5H); MS (EI, m/z) 551 (M^+, 0.2), 536 (0.1), 460 (0.1), 424 (17), 91 (100); HRMS (EI, m/z) for $C_{19}H_{27}NSiI_2$, calcd 551.0003, found 551.0037. **5b**: IR (neat) ν 1634, 1246, 1202 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.04 (s, 9H), 1.20−2.15 (m, 5H), 2.15−2.37 (m, 1 H), 2.79−3.07 (m, 2 H), 3.00 (d, J = 15.8 Hz, 1 H), 3.22 (d, J = 13.6 Hz, 1 H), 3.57 (d, J = 15.8 Hz, 1 H), 3.95 (d, J = 13.6 Hz, 1 H), 4.45−4.62 (m, 1 H), 5.56 (s, 1 H), 7.16−7.40 (m, 5 H); MS (EI, m/z) 425 (M^+, 5), 410 (7), 352 (8), 298 (96), 256 (6), 225 (4), 91 (100), 73; HRMS (EI, m/z) for $C_{19}H_{28}NSiI$, calcd 425.1035, found 425.1051.

(1*S,4*R**,8*S**,11*R**)-3-Benzyl-1-formyl-3-azatricyclo-[6.2.1.0^{4,11}]undecan-9-one (6a).** A solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (177.9 mg, 0.61 mmol), BuLi (1.61 M solution in hexane, 0.70 mL, 1.13 mmol), and **1a** (49.6 mg, 0.17 mmol) in THF (1.5 mL)] was stirred at rt for 18 h under an atmosphere of carbon monoxide. To the solution at 0 °C was added 10% HCl (1.0 mL). After the solution was stirred at rt for 2 h, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by TLC (AcOEt−hexane, 1:10) to afford 14.2 mg (30%) of **6a** as a colorless oil: IR (neat) ν 1740, 1720 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 1.21−1.75 (m, 4 H), 2.02 (d, J = 18.0 Hz, 1 H), 1.97−2.13 (m, 1 H), 2.24−2.39 (m, 2 H), 2.53 (d, J = 9.5 Hz, 1 H), 2.57 (m, 1 H), 2.74 (d, J = 9.5 Hz, 1 H), 2.96 (d, J = 13.2 Hz, 1 H), 3.00 (dd, J = 7.3, 10.0 Hz, 1 H), 3.16 (dd, J = 2.2, 18.0, Hz, 1 H), 4.04 (d, J = 13.2 Hz, 1 H), 7.16−7.40 (m, 5 H), 9.64 (s, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.3, 200.4, 138.5, 128.4, 128.2, 127.1, 63.0, 62.3, 56.1, 55.7, 44.7, 44.5, 43.4, 25.5, 22.8, 15.8; MS (EI, m/z) 283 (M^+, 52), 255 (35), 226 (48), 206 (15), 192 (54), 91 (100); HRMS (EI, m/z) for $C_{18}H_{21}NO_2$, calcd 283.1572, found 283.1576. Anal. Calcd for $C_{18}H_{21}NO_2$: C, 76.30; H, 7.47; N, 4.90. Found: C, 76.52; H, 7.55; N, 4.75.

(1*R,4*R**,8*S**,11*R**)-3-Benzyl-1-formyl-10-methyl-3-azatricyclo[6.2.1.0^{4,11}]undecan-9-one (6b).** A solution of a zirconacycle [prepared from Cp_2ZrCl_2 (78.2 mg, 0.27 mmol), BuLi (1.65 M solution in hexane, 0.32 mL, 0.52 mmol), and **1b** (49.9 mg, 0.21 mmol) in THF (1.5 mL)] was stirred at rt for 9.5 h under an atmosphere of carbon monoxide. To the solution at 0 °C was added 10% HCl (1.0 mL). After the solution was stirred at rt for 16 h, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt−hexane, 1:10, 1:5, 1:1) to afford 11.3 mg (18%) of **6b** as a colorless oil: IR (neat) ν 1740, 1723 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.86 (d, J = 7.0 Hz, 3 H), 1.21−1.65 (m, 4 H), 1.93−2.11 (m, 1 H), 2.25 (d, J = 10.3 Hz, 1 H), 2.31−2.57 (m, 3 H), 2.87 (d, J = 13.1 Hz, 1 H), 2.91 (d, J =

10.3 Hz, 1 H), 2.95 (q, J = 7.0 Hz, 1 H), 2.96 (ddd, J = 6.6, 6.6, 7.1 Hz, 1 H), 4.02 (d, J = 13.1 Hz, 1 H), 7.18–7.39 (m, 5 H), 9.70 (s, 1 H); MS (EI, m/z) 297 (M^+, 26), 280 (6), 269 (17), 240 (24), 206 (21), 190 (6), 106 (18), 91 (100); HRMS(EI, m/z) for $C_{19}H_{23}NO_2$, calcd 297.1729, found 297.1735. Anal. Calcd for $C_{19}H_{23}NO_2$: C, 76.74; H, 7.79; N, 4.71. Found: C, 76.86; H, 8.07; N, 4.59.

(3a*R,7a*R**)-1-Benzyl-4-formyl-3-((*Z*)-(trimethylsilyl)-methylene)perhydroindole (11).** To a stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (254.1 mg, 0.78 mmol), BuLi (1.62 M solution in hexane, 1.0 mL, 1.62 mmol), and **1a** (200.0 mg, 0.67 mmol) in THF (1.5 mL)] was added ^{t}BuNC (0.10 mL, 0.87 mmol) at rt, and the solution was stirred at rt for 8.5 h. To the solution was added 50% AcOH (1.0 mL) at rt, and the solution was stirred at rt for 10 h. The resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over anhydrous Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:20) to afford 145.9 mg (66%) of **11** as a colorless oil: IR (neat) ν 1720, 1631 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.00 (s, 9 H), 1.20–1.94 (m, 6 H), 2.56–2.89 (m, 3 H), 2.95 (d, J = 15.5 Hz, 1 H), 3.22 (d, J = 13.5 Hz, 1H), 3.55 (d, J = 15.5 Hz, 1 H), 4.00 (d, J = 13.5 Hz, 1 H), 5.27 (s, 1 H), 7.18–7.47 (m, 5 H), 9.73 (d, J = 2.2 Hz, 1 H); MS (EI, m/z) 327 (M^+, 21), 312 (6), 298 (44), 254 (25), 236 (6), 91 (100); HRMS (EI, m/z) for $C_{20}H_{29}NOSi$, 327.2019, found 327.2007. Anal. Calcd for $C_{20}H_{29}NOSi$: C, 73.34; H, 8.92; N, 4.28. Found: C, 73.35; H, 8.99; N, 4.32.

1-Benzyl-3-((*Z*)-deuterio(trimethylsilyl)methylene)-4-methylpyrrolidine (3c-D, Table 1, run 7). To a −78 °C stirred solution of zirconacycle **2c** [prepared from Cp_2ZrCl_2 (73.7 mg, 0.25 mmol), BuLi (1.65 M solution in hexane, 0.30 mL, 0.50 mmol), and **1c** (49.6 mg, 0.19 mmol) in THF (1.5 mL)] was added trifluoroacetic acid (0.54 M solution in benzene, 0.35 mL, 0.19 mmol). After the solution was stirred at −78 °C for 5 h, 10% DCl/D_2O (1.0 mL) was added, and the solution was stirred at rt for 30 min. The resultant mixture was basified with K_2CO_3 and extracted with AcOEt, and the organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:20) to afford 49.5 mg (100%) of **3c-D** as a colorless oil: IR (neat) ν 1630, 1600 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.06 (s, 9H), 1.07 (d, J = 6.8 Hz, 3 H), 1.98 (dd, J = 8.7, 8.7 Hz, 1 H), 2.57–2.71 (m, 1 H), 2.95 (dd, J = 7.4, 8.7 Hz, 1 H), 3.02 (dd, J = 2.0, 13.8 Hz, 1 H), 3.54 (d, J = 13.8, 1 H), 3.53 (d, J = 12.9 Hz, 1 H), 3.66 (d, J = 12.9 Hz, 1 H), 7.16–7.37 (m, 5 H); MS (EI, m/z) 260 (M^+), 259 (23), 187 (29), 169 (11), 105 (25), 91 (100); HRMS (EI, m/z) for $C_6H_{24}NSiD$, calcd 260.1819, found 260.1802.

(3a*R,7a*R**)-1-Benzyl-3-((*Z*)-deuterio(trimethylsilyl)-methylene)perhydroindole (3a-D).** To a 0 °C stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (64.5 mg, 0.22 mmol), BuLi (1.62 M solution in hexane, 0.26 mL, 0.42 mmol), and **1a** (50.3 mg, 0.17 mmol) in THF (1.5 mL)] was added propionic acid (0.013 mL, 0.17 mmol), and the solution was stirred at 0 °C for 1 h. To the solution at 0 °C was added 10% DCl/D_2O (1.0 mL), and the resultant mixture was stirred at rt for 30 min. The mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:60) to afford 22.8 mg (45%) of **3a-D** as a colorless oil: IR (neat) ν 1626, 1246 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 0.03 (s, 9 H), 1.00–2.10 (m, 8 H), 2.22–2.66 (m, 1 H), 2.66–2.88 (m, 1 H), 3.07 (d, J = 15.0 Hz, 1 H), 3.51 (d, J = 13.6 Hz, 1 H), 3.66 (d, J = 15.0 Hz, 1 H), 3.95 (d, J = 13.6 Hz, 1 H), 7.22–7.39 (m, 5 H); MS (EI, m/z) 300 (M^+, 21), 285 (6), 227 (42), 209 (10), 91 (100), 73 (25); HRMS (EI, m/z) for $C_{19}H_{28}DNSi$, calcd 300.2132, found 300.2109.

(3a*R,4*S**,7a*R**)-1-Benzyl-4-formyl-3-((*E*)-iodo(trimethylsilyl)methylene)perhydroindole (12).** To a at 0 °C stirred solution of zirconacycle **2a** [prepared from Cp_2ZrCl_2 (64.4 mg, 0.22 mmol), BuLi (1.62 M solution in hexane, 0.27 mL, 0.43 mmol), and **1a** (50.1 mg, 0.17 mmol) in THF (1.5 mL)] was added ^{t}BuNC (0.03 mL, 0.26 mmol), and the solution was stirred at rt for 18 h. To the solution at −78 °C was added I_2 (230.2 mg, 0.88 mmol), and the solution was stirred at rt for 15 min. To the 0 °C solution was added 20% $Na_2S_2O_3$ (1.0 mL), and the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:60) to afford 32.2 mg (42%) of **12** as an oil: IR (neat) ν 1712, 1680 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.21 (s, 9 H), 1.26–1.47 (m, 2 H), 1.54–1.78 (m, 2 H), 1.98–2.11 (m, 1 H), 2.32–2.45 (m, 1 H), 2.62–2.70 (m, 1 H), 2.76 (d, J = 14.6 Hz, 1 H), 2.97–3.09 (m, 1 H), 3.05 (d, J = 12.5 Hz, 1 H), 3.29 (dd, J = 4.0, 7.4 Hz, 1 H), 3.51 (d, J = 14.6 Hz, 1 H), 4.04 (d, J = 12.5 Hz, 1 H), 7.19–7.42 (m, 5 H), 9.56 (d, J = 1.5 Hz, 1 H); MS (EI, m/z) 453 (M^+, 1), 438 (2), 425 (21), 362 (10), 326 (42), 298 (25), 235 (21), 120 (39), 91 (100), 73; HRMS (EI, m/z) for $C_{20}H_{28}INOSi$, calcd 453.0985, found 453.0986.

(3a*R,7a*R**)-1-Benzyl-3a-methyl-3-((*Z*)-(trimethylsilyl)-methylene)perhydroindole (3d).** To a 0 °C stirred solution of zirconacycle **2d** [prepared from Cp_2ZrCl_2 (52.6 mg, 0.18 mmol), BuLi (1.65 M solution in hexane, 0.21 mL, 0.35 mmol), and **1d** (45.0 mg, 0.14 mmol) in THF (1.5 mL)] was added 10% HCl (1.0 mL). After the solution was stirred at rt for 30 min, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:10) to afford 38.3 mg (87%) of **3d** as a colorless oil: IR (neat) ν 1632 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ −0.05 (s, 9 H), 0.83–1.81 (m, 8 H), 2.16 (dd, J = 3.4, 3.4 Hz, 1 H), 1.03 (s, 3 H), 2.79 (dd, J = 2.2, 15.0 Hz, 1 H), 3.06 (d, J = 13.4 Hz, 1 H), 3.60 (dd, J = 2.2, 15.0 Hz, 1 H), 4.01 (d, J = 13.4 Hz, 1 H), 5.04 (dd, J = 2.2, 2.9 Hz, 1 H), 7.18–7.31 (m, 5 H); MS (EI, m/z) 313 (M^+, 7) 298 (5), 240 (40), 222 (4), 149 (6), 105 (5), 91 (46), 73 (15), 58 (27), 43 (100); HRMS (EI, m/z) for $C_{20}H_{31}NSi$, calcd 313.2226, found 313.2202. Anal. Calcd for $C_{20}H_{31}NSi$: C, 76.61; H, 9.97; N, 4.47. Found: C, 76.78; H, 10.06; N, 4.45.

(3a*S,7a*R**)-1-Benzyl-3a-(hydroxymethyl)-3-((*Z*)-deuterio(trimethylsilyl)methylene)perhydroindole (15-D).** A solution of zirconacycle **2d** [prepared from Cp_2ZrCl_2 (61.4 mg, 0.21 mmol), BuLi (1.65 M solution in hexane, 0.24 mL, 0.40 mmol), and **1d** (50.0 mg, 0.16 mmol) in THF (1.5 mL)] was stirred at rt for 3 h under an atmosphere of oxygen. To the solution at 0 °C was added 10% DCl/D_2O (1.0 mL). After stirring at rt for 30 min, the resultant solution was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:4) to afford 28.9 mg (55%) of **15-D** as a colorless oil: IR (neat) ν 3416, 1623 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.08 (s, 9 H), 1.00–1.30 (m, 8 H), 1.33–1.46 (m, 1 H), 2.97 (dd, J = 4.7, 9.6 Hz, 1 H), 3.30 (d, J = 14.6 Hz, 1 H), 3.34 (d, J = 9.7 Hz, 1 H), 3.51 (d, J = 14.6 Hz, 1 H), 3.63 (d, J = 9.7 Hz, 1 H), 3.65 (d, J = 13.1 Hz, 1 H), 3.78 (d, J = 13.1 Hz, 1 H), 7.20–7.34 (m, 5 H); MS (EI, m/z) 330 (M^+, 4), 329 (5), 315 (2), 299 (10), 257 (13), 239 (13) 91 (100), 73 (35); HRMS (EI, m/z) for $C_{20}H_{30}NOSiD$, calcd 330.2237, found 330.2241.

(4*R,9*S**)-3-Benzyl-12-(trimethylsilyl)-3-azatricyclo-[7.3.0.0^{4,9}]dodec-12-en-11-one (16) and (3a*S**,7a*R**)-1-Benzyl-3a-(hydroxymethyl)-3-((*Z*)-(trimethylsilyl)methylene)-perhydroindole (15).** A solution of zirconacycle **2d** [prepared from Cp_2ZrCl_2 (61.4 mg, 0.21 mmol), BuLi (1.63 M solution in hexane, 0.25 mL, 0.40 mmol), and **1d** (50.0 mg, 0.16 mmol) in THF (1.5 mL)] was stirred at rt for 66 h under an atmosphere of carbon monoxide. To the solution at 0 °C was added 10% HCl (1.0 mL). After stirring at rt for 30 min, the resultant mixture was basified with K_2CO_3 and extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:8, 1:4) to afford 21.4 mg (39%) of **16** and 17.7 mg (34%) of **15** as colorless oils: **16**: IR (neat) ν 1698, 1618 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.19 (s, 9 H), 0.90–2.03 (m, 8 H), 2.11 (d, J = 16.7 Hz, 1 H), 2.35 (d, J = 16.7 Hz, 1 H), 2.45 (br s, 1 H), 3.05 (d, J = 18.3 Hz, 1 H), 3.24 (d, J = 13.8 Hz, 1 H), 4.00 (d, J = 18.3 Hz, 1 H), 4.18 (d, J = 13.8 Hz, 1 H), 7.28–7.39 (m, 5 H); MS (EI, m/z) 339 (M^+, 165), 324 (11), 311 (11), 296 (9), 266 (6), 248 (42),

226 (17), 91 (100), 73 (42); HRMS (EI, *m/z*) for $C_{21}H_{29}NOSi$, calcd 339.2018, found 339.2032. Anal. Calcd for $C_{21}H_{29}NOSi$: C, 74.28; H, 8.61; N, 4.13. Found: C, 74.28; H, 8.69; N, 4.01. **15**: IR (neat) ν 3403, 1630 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.08 (s, 9 H), 0.88–1.76 (m, 9 H), 2.99 (dd, J = 4.8, 9.5 Hz, 1 H), 3.28 (dd, J = 2.6, 14.6 Hz, 1H), 3.34 (d, J = 9.5 Hz, 1H), 3.55 (dd, J = 2.6, 14.6 Hz, 1 H), 3.62 (d, J = 9.5 Hz, 1 H), 3.66 (d, J = 13.2 Hz, 1 H), 3.78 (d, J = 13.2 Hz, 1 H), 5.35 (dd, J = 2.6, 2.6 Hz, 1 H), 7.24–7.37 (m, 5 H); MS (EI, *m/z*) 329 (M^+, 6), 328 (6), 314 (4), 312 (3), 298 (22), 286 (2), 256 (36), 238 (32), 120 (6), 91 (100), 73 (31); HRMS (EI, *m/z*) for $C_{20}H_{31}NOSi$, calcd 329.2175, found 329.2146. Anal. Calcd for $C_{20}H_{31}NOSi$: C, 72.89; H, 9.48; N, 4.25. Found: C, 72.72; H, 9.49; N, 3.98.

(3a*S,7a*R**)-1-Benzyl-3a-(acetoxymethyl)-3-((*Z*)-(trimethylsilyl)methylene)perhydroindole (17).** To a stirred solution of **15** (4.5 mg, 0.014 mmol) in CH_2Cl_2 (1.0 mL) containing pyridine (0.045 mL, 0.56 mmol) was added acetic anhydride (0.026 mL, 0.28 mmol), and the solution was stirred at rt for 12 h. To the solution was added saturated $NaHCO_3$ (1.0 mL), and the resultant solution was extracted with AcOEt. The organic layer was washed with brine and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography (AcOEt–hexane, 1:4) to afford 3.3 mg (63%) of **17** as a colorless oil: IR (neat) 1742 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 0.02 (s, 9 H), 1.26–1.79 (m, 8 H), 2.03 (s, 3 H), 2.69 (dd, J = 5.1, 5.1 Hz, 1 H), 3.14 (dd, J = 2.6, 14.7 Hz, 1 H), 3.37 (d, J = 13.6 Hz, 1 H), 3.44 (dd, J = 2.6, 15.0 Hz, 1 H), 3.91 (d, J = 13.6 Hz, 1 H), 4.02 (d, J = 11.0 Hz, 1 H), 4.17 (d, J = 11.0 Hz, 1H), 5.24 (dd, J = 2.6, 2.6 Hz, 1 H), 7.23–7.33 (m, 5 H); MS (EI, *m/z*) 371 (M^+, 5), 356 (2), 328 (1), 312 (4), 298 (73), 280 (7), 91 (100), 73 (28), 59 (10), 43 (17); HRMS (EI, *m/z*) for $C_{22}H_{33}NO_2Si$, calcd 371.2280, found 371.2292.

Supplementary Material Available: Copies of ^1H NMR spectra of **1a**, **3a-D$_2$**, **5a**, **5b**, **3c-D**, **3a-D**, **12**, **15-D**, and **17** (9 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from ACS; see any current masthead page for ordering information.