April 1997 Chem. Pharm. Bull. 45(4) 651—658 (1997) 651

Dirhodium(II)-Catalyzed Intramolecular Carbon–Hydrogen Insertion Reaction of α-Diazoketones: Synthesis of 7-Silyloxyoctahydrobenzo[*b*]furan-2-ones

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Received November 18, 1996; accepted December 8, 1996

A dirhodium(II)-catalyzed intramolecular C–H insertion reaction of 2-oxygen-substituted cyclohexyl diazoacetoacetates 1a—f was investigated. In contrast to the *trans*-2-methoxy- 1a and *trans*-2-(*p*-methoxybenzyloxy)-cyclohexyl derivatives 1b, which, upon treatment with 1 mol% dirhodium(II) tetraacetate in boiling benzene, gave a complex mixture, the *trans*-2-(*tert*-butyldimethylsilyloxy)cyclohexyl derivative 1c gave, in addition to the β-lactone 3c (16%), *cis*- and *trans*-fused octahydrobenzo[*b*]furan-2-ones 2c in 22 and 18% yields, respectively. Similar treatment of the *cis*-isomer 1d gave the β-lactone 3d as the major product (34%) and *cis*- and *trans*-fused γ-lactones 2d (7 and 18% yields, respectively) as minor products. The (1*R,2*R**,3*R**)-3-benzyloxy-2-(*tert*-butyldimethylsilyloxy)cyclohexyl derivative 1e gave the γ-lactones 2e in 75% combined yield as a 5:2 mixture of *cis*- and *trans*-fused isomers, while the (1*R**,2*S**,3*R**)-isomer 1f afforded the *trans*-fused γ-lactone 2f in 62% yield as a single product.**

Key words dirhodium(II) tetraacetate; carbon–hydrogen insertion reaction; regioselectivity; octahydrobenzo[*b*]furan-2-one; β-lactone

A dirhodium(II)-catalyzed intramolecular C–H insertion reaction of α-diazocarbonyl compounds[1] is emerging as a valuable tool for the construction of carbo- and heterocyclic compounds. In connection with our synthetic studies on avermectin antibiotics,[2,3] we have investigated the dirhodium(II)-catalyzed intramolecular C–H insertion reaction of 2-oxygen-substituted cyclohexyl diazoacetoacetates **1** in the hope of obtaining 7-oxygen-substituted octahydrobenzofuran-2-ones **2**. In the reaction of **1** there are theoretically four possible reaction pathways leading to isomeric γ-lactones **2** and **3**,[4] β-lactones **4**,[5] and oxonium ylides **5**.[6] To control the regiochemistry and, if possible, the stereochemistry of the reaction, we planned to examine the effect of oxygen-substituents in the cyclohexyl diazoacetoacetates. In this paper, we describe results obtained with more readily accessible 2-oxygen-substituted cyclohexyl diazoacetoacetates **1a**—**f**, in which the diazoacetoacetoxy group occupies an equatorial position.

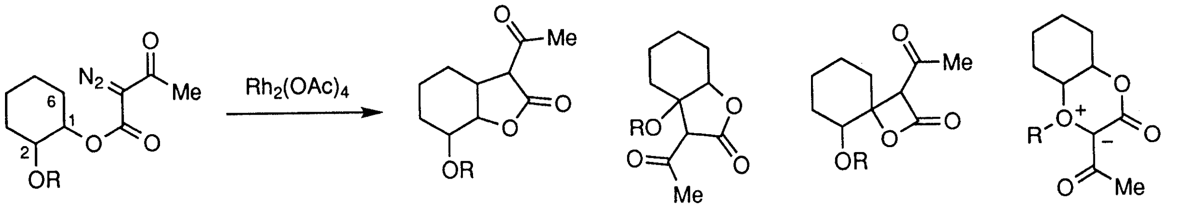
Results

We began our investigations by examining the reaction of diazoacetoacetates **1a**—**d**. The *trans*-isomers **1a**—**c** and the *cis*-isomer **1d** were readily prepared starting from commercially available cyclohexene oxide and *cis*-1,2-cyclohexanediol, respectively (see Chart 1 and Experimental). The ^{1}H-NMR spectra of **1a**—**c** showed the 1,2-diaxial nature of the H-1 and H-2 protons ($J_{1,2}=8.0$—9.0 Hz), confirming that both the oxygen-substituents adopt equatorial positions. On the other hand, the ^{1}H-NMR spectrum of the *cis*-isomer **1d** indicated the equatorial nature of H-2 ($J_{1,2}=2.7$, $J_{2,3}=6.6$, 2.7 Hz) and the axial disposition of H-1 ($J_{1,2}=2.7$, $J_{1,6}=8.7$, 2.7 Hz), suggesting that the 2-*tert*-butyldimethylsilyloxy (TBDMS-oxy) and diazoacetoacetoxy groups occupy axial and equatorial positions, respectively.

In general, a solution of a diazoacetoacetate **1** in benzene was added to a boiling benzene solution of 1 mol% of dirhodium(II) tetraacetate [$Rh_2(OAc)_4$] *via* a syringe pump over a period of 4—6 h. After removal of the solvent, the crude material was chromatographed on silica gel.

Treatment of the *trans*-2-methoxy- **1a** and 2-(*p*-methoxybenzyloxy)cyclohexyl derivatives **1b** in this manner gave a complex mixture in each case; the γ-lactone **2b** was isolated in only 4% yield as a mixture of two diastereoisomers from the reaction mixture of **1b**. The structural assignment of **2b** rests largely on the basis of spectral data (see Experimental).

In contrast, the reaction of the *trans*-2-(*tert*-butyldimethylsilyloxy)cyclohexyl derivative **1c** under the same conditions gave the β-lactone **4c** (16%), and the *cis*- and *trans*-fused γ-lactones **2c** in 22 and 18% yields, respectively. The structure of the β-lactone **4c** was assigned mainly on the basis of its IR spectrum (1825 cm^{-1}). The stereochemistry of *trans*-**2c** was determined by comparison of the ^{1}H-NMR coupling constants with those of the



1 **2** **3** **4** **5**

(eq. 1)

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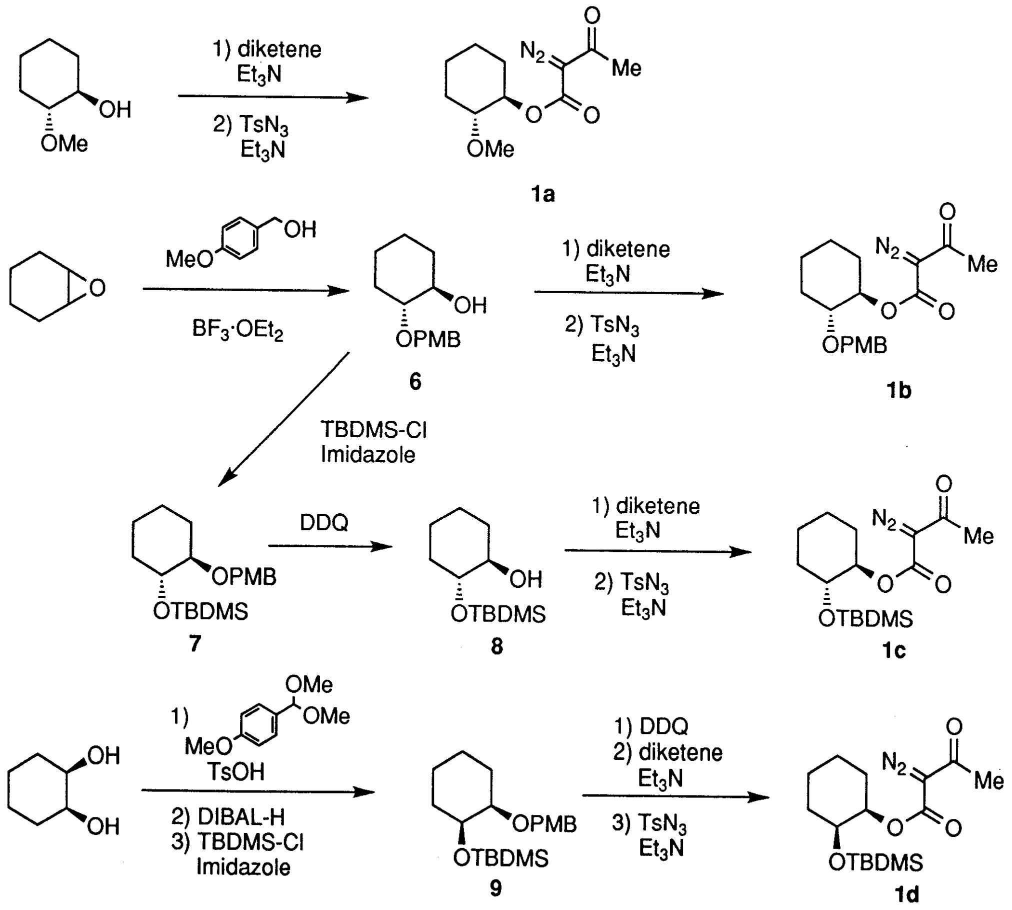


Chart 1

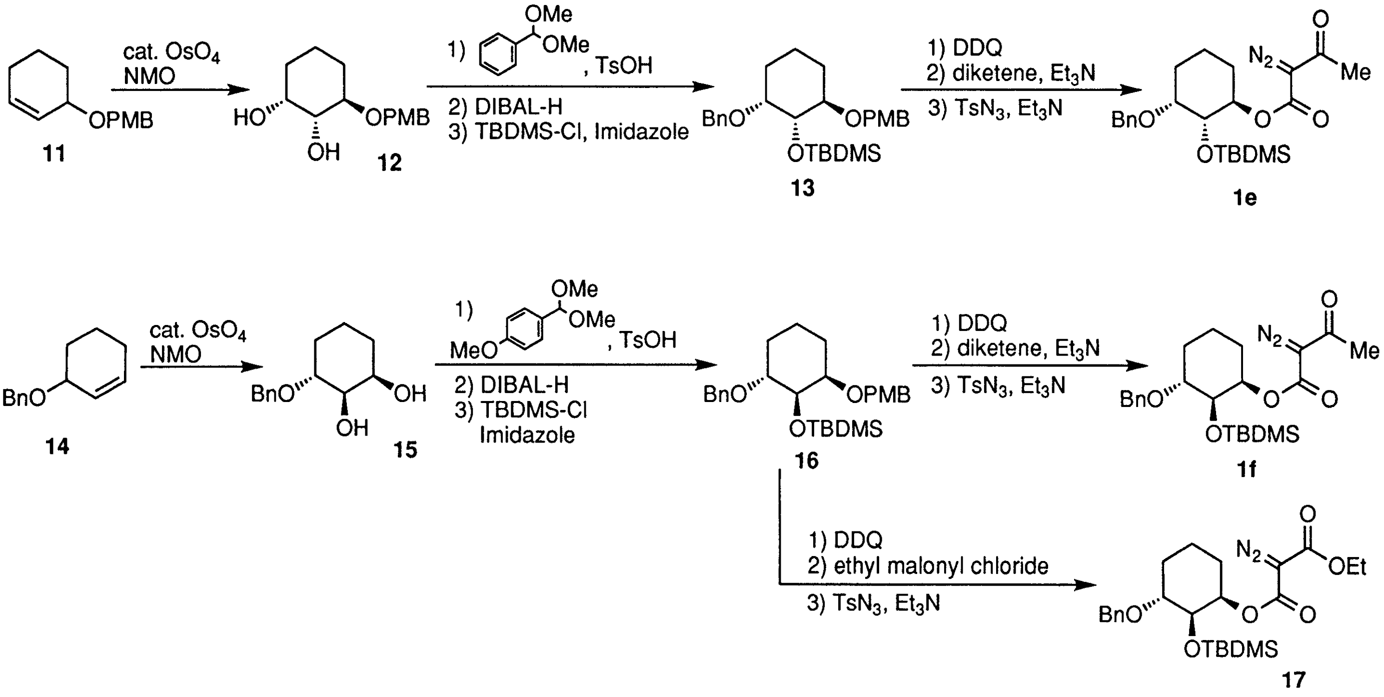
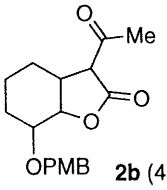
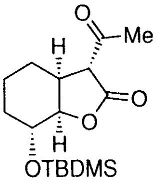
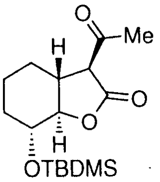
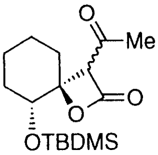
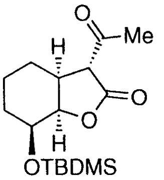
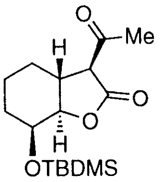
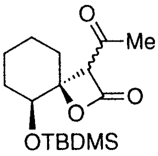
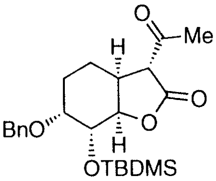
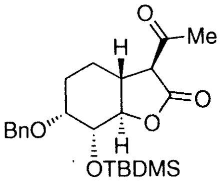
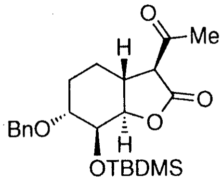
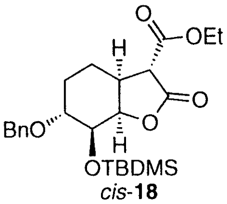
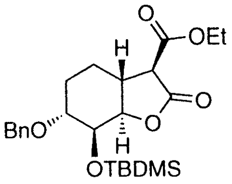


Chart 2

related bicyclic *trans*-fused γ-lactone **10** derived from menthyl diazoacetoacetate[4a]: the observed coupling constants between H-3 and H-3a (12.5 Hz) and between H-3a and H-7a (10.6 Hz) in *trans*-**2c** were in good agreement with the reported values for **10** ($J_{3,3a}=12.4$, $J_{3a,7a}=10.7$ Hz) (Table 2). The stereochemistry of *cis*-**2c** was deduced from differential nuclear Overhauser effect (NOE) experiments (Fig. 1); irradiation of the signal due to H-3 caused a 12% enhancement in the intensity of the signal due to H-7, and 5.5—7% enhancement was observed between

Table 1. Dirhodium(II)-Catalyzed Intramolecular C–H Insertion Reaction of α-Diazoketones

Entry	α-Diazoketone	Conditions[a]	Products (Yields)
1	**1a**	Benzene reflux, 5 h	A complex mixture
2	**1b**	Benzene reflux, 5 h	 **2b** (4%)
3	**1c**	Benzene reflux, 6 h	 *cis*-**2c** (22%)  *trans*-**2c** (18%)  **4c** (16%)[b]
4	**1d**	Benzene reflux, 5 h	 *cis*-**2d** (7%)  *trans*-**2d** (18%)  **4d** (34%)[c]
5	**1e**	Benzene reflux, 4 h	 *cis*-**2e**  *trans*-**2e** (75% as a 5:2 mixture of *cis*-**2e** and *trans*-**2e**)
6	**1f**	Benzene reflux, 4 h	 *trans*-**2f** (62%)
7	**1f**	Toluene reflux, 2 h	*trans*-**2f** (48%)
8	**17**	Benzene reflux, 5 h	 *cis*-**18**  *trans*-**18** (31% as a 1:7 mixture of *cis*-**18** and *trans*-**18**)

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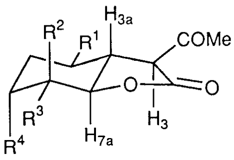
[a] Reactions were carried out with 1 mol% of $Rh_2(OAc)_4$. [b] A 4:1 mixture of two diastereoisomers. [c] A 2:1 mixture of two diastereoisomers.

H-3a and H-7a. A similar treatment of the 1,2-*cis*-isomer **1d** with $Rh_2(OAc)_4$ gave the β-lactone **4d** (34%), and the *cis*- and *trans*-fused γ-lactones **2d** in 7 and 18% yields, respectively.

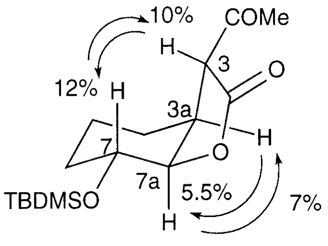
Since the 2-TBDMS-oxy group alone could not prevent β-lactone formation, we next investigated the reaction of the diazoacetoacetates **1e** and **1f** having an additional axial benzyloxy group at the 3-position. Two isomeric compounds **1e** and **1f** were synthesized as shown in Chart 2. Thus, 3-(*p*-methoxybenzyloxy)cyclohexene (**11**) was stereoselectively oxidized by a catalytic amount of osmium tetroxide and *N*-methylmorpholine *N*-oxide (NMO) to give the *syn*-diol **12**,[7,8] which was allowed to react with benzaldehyde dimethylacetal in the presence of *p*-toluenesulfonic acid, followed by ring-opening of the cyclic acetal with diisobutylaluminum hydride (DIBAL-H)[9] and silylation to give **13** in 57% yield. Deprotection of the *p*-methoxybenzyl (PMB) group of **13** with 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ)[10] gave the mono alcohol, which was esterified with diketene, followed by

Table 2. The Vicinal Coupling Constants ($J_{3,3a}$, $J_{3a,7a}$) of *trans*-Fused γ-Lactones



γ-Lactone	R^1	R^2	R^3	R^4	$J_{3,3a}$ (Hz)	$J_{3a,7a}$ (Hz)
trans-**2c**	H	H	OTBDMS	H	12.5	10.6
trans-**2d**	H	OTBDMS	H	H	13.0	11.1
trans-**2e**	H	H	OTBDMS	OBn	12.7	11.1
trans-**2f**	H	OTBDMS	H	OBn	12.9	11.2
10[a]	Me	H	iso-Pr	H	12.4	10.7

[a] Ref. 4*a*.



cis-**2c**

Fig. 1. The Result of NOE Experiments on *cis*-**2c**

diazotransfer reaction with *p*-toluenesulfonyl azide to afford **1e**. The stereochemistry was assigned on the basis of the ^{1}H-NMR spectrum, which indicated that the diazoacetoacetoxy and silyloxy groups both occupy equatorial positions and the benzyloxy group takes an axial position (see Experimental). Repetition of the same sequence starting from 3-(benzyloxy)cyclohexene (**14**)[8] produced **1f**, whose ^{1}H-NMR spectrum showed that the benzyloxy and silyloxy groups adopt axial positions and the diazoacetoacetoxy group takes an equatorial position (see Experimental). The diazomalonate **17** was also prepared from **16** in a similar manner.

The diazoacetoacetate **1e**, upon treatment with $Rh_2(OAc)_4$, gave an inseparable 5 : 2 mixture of *cis*- and *trans*-fused γ-lactones **2e** in 75% combined yield. On the other hand, a similar treatment of the diazoacetoacetate **1f** in boiling benzene proceeded smoothly to give the *trans*-fused γ-lactone **2f** as a single isomer in 62% yield. When the same reaction was carried out in boiling toluene, the yield of *trans*-**2f** was reduced to 48%. The diazomalonate **17** gave the corresponding *cis*- and *trans*-fused γ-lactones **18** in 31% combined yield and in a ratio of 1 : 7.

Discussion

Taking into account the results of earlier studies on the C–H insertion reactions catalyzed by dirhodium(II) catalysts, it would appear that the most likely mechanism for the reactions of diazoacetates would involve initial overlap of the metal carbene's *p*-orbital with the σ-orbital of the reacting C–H bond, which leads to new C–C and C–H bond formation with the carbene carbon as the metal dissociates.[4a,11] In the C–H insertion reaction of the cyclohexyl diazoacetates, γ-lactone formation appears to be favored, although there are some exceptions, involving β-lactone formation.[5] However, the regioselectivity becomes complicated if an alkoxy group is introduced near the site of insertion, because the oxygen atom itself[6] and the C–H bond adjacent to the oxygen atom[12] become the preferred sites of reaction. Indeed, the 2-methoxy and 2-(*p*-methoxybenzyl)oxy derivatives **1a, b** each gave a complex mixture, possibly as a result of the reaction of the carbenoids with the ether oxygen atom. To overcome such complications, we introduced a bulky TBDMS-oxy group at the C-2 position; this was expected to cause a reduction of the reactivity at the ether oxygen atom as well as the C–H bond at the C-2 position. As expected, the 2-TBDMS-oxy derivatives **1c, d** gave the γ-lactones in moderate yields, but the β-lactone formation could not be prevented. The regioselective formation of the γ-lactones was achieved by introduction of an additional axial benzyloxy group at the C-3 position, as seen in the cases of **1e, f** and **17**. The axial 3-benzyloxy group may destabilize the transition state A leading to the β-lactone by steric interference with the dirhodium complex.

The diastereoselectivity of the C–H insertion reaction of cyclohexyl diazoacetates is known to be influenced by the conformation of the diazoacetoxy group.[5] When this group occupies an axial position, the insertion reaction occurs with the equatorial C–H bond to give the *cis*-fused γ-lactones. However, in the case of the equatorial diazoacetoxy group, the stereochemical outcome is less predictable. For example, *trans*-4-*tert*-butylcyclohexyl diazoacetate[5] and menthyl diazoacetoacetate[4a] having an equatorial diazoacetoxy group give only the *trans*-fused γ-lactones, while *trans*-4-methylcyclohexyl diazoacetate[4c] affords a mixture of the *cis*- and *trans*-fused γ-lactones.[13] The reaction of **1c**—**e** in which the diazoacetoacetoxy group occupies an equatorial position, gave a mixture of the *cis*- and *trans*-fused γ-lactones. On the other hand, **1f** and **17** possessing an equatorial diazoacetoacetoxy or diazomalonyloxy group, an axial 2-TBDMS-oxy and axial 3-benzyloxy groups, afforded exclusively or predominantly the *trans*-fused γ-lactones as a result of the preferential equatorial C–H insertion reaction at the C-6 position. The decrease of the formation of the *cis*-fused γ-lactones in the reaction of **1f** as well as **17** can be rationalized in terms of the steric factor: the transition state B leading to the *cis*-fused γ-lactone seems to be disfavored by steric interference between the axial 2-TBDMS-oxy group and dirhodium complex, which is absent in the transition state C leading to the *trans*-fused γ-lactone.

In summary, the present work has revealed that steric effects of neighboring substituents play an important role in determining the regio- and stereoselectivity in the dirhodium(II)-catalyzed intramolecular C–H insertion reactions of the 2-oxygen-substituted cyclohexyl diazoacetoacetates. It may be anticipated on this basis that the axial-diazoacetoacetates will show different behavior. Related work aimed at exploring this general area is in progress.

Experimental

All melting points were uncorrected. IR spectra were recorded using a

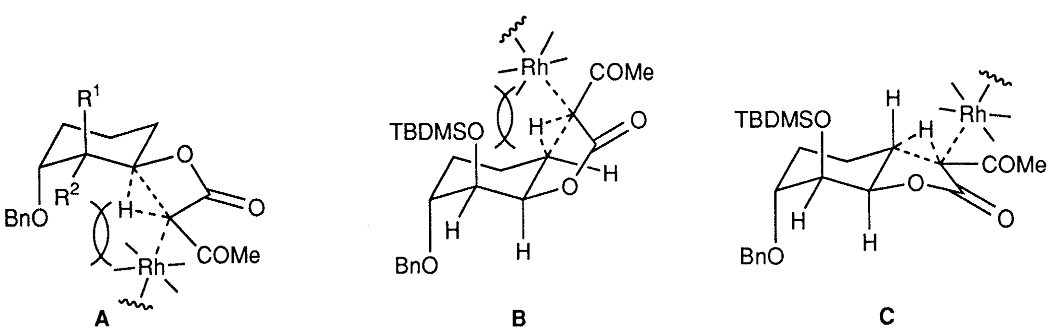


Fig. 2

JASCO IR-1 spectrophotometer. ^{1}H-NMR spectra were determined with a JEOL JNM-PMX 60 (60 MHz), JEOL JNM-EX 270 (270 MHz), or Varian XL-300 (300 MHz) spectrometer using $CDCl_3$ as a solvent and tetramethylsilane as an internal standard. ^{13}C-NMR spectra were recorded on either a JEOL JNM-EX 270 (68 MHz) or a Varian XL-300 (75 MHz) spectrometer using $CDCl_3$ as a solvent and are reported in ppm using the solvent resonance as an internal standard (77.0 for $CDCl_3$). All ^{13}C-NMR spectra were determined with complete proton decoupling. High-resolution mass spectra (Exact MS and Exact FAB-MS) were obtained with a JEOL JMS-SX 102A QQ instrument at 20 eV. Column chromatography was carried out on Silica gel 60 PF_{254} (Nacalai Tesque, Inc.) under pressure.

***trans*-2-Methoxycyclohex-1-yl Diazoacetoacetate (1a)** This compound was prepared according to the reported procedure.[14] Diketene (237 mg, 2.82 mmol) and triethylamine (517 mg, 5.12 mmol) were added to a solution of *trans*-2-methoxy-1-cyclohexanol[15] (330 mg, 2.56 mmol) in tetrahydrofuran (THF) (10 ml) at 0 °C. The mixture was stirred at room temperature for 9 h, then poured into H_2O (10 ml) and extracted with Et_2O (3 × 10 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 7 : 1) to give the corresponding acetoacetate (385 mg, 71%) as a colorless oil. The resulting acetoacetate (312 mg, 1.46 mmol) was dissolved in CH_3CN (10 ml), then triethylamine (295 mg, 2.92 mmol) and *p*-toluenesulfonyl azide (318 mg, 1.46 mmol) were added at room temperature. The mixture was stirred for 11 h, then poured into H_2O (30 ml), and extracted with Et_2O (3 × 20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 10 : 1) to give **1a** (329 mg, 94%) as a colorless oil. IR (CCl_4) cm^{-1}: 2120 ($C=N_2$), 1710, 1655. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.2—1.5 (4H, m, 2 × CH_2), 1.6—1.8 (2H, m, CH_2), 2.0—2.2 (2H, m, CH_2), 2.49 (3H, s, CH_3CO), 3.18 (1H, ddd, J = 13.2, 9.2, 4.5 Hz, C_2-H), 3.37 (3H, s, OCH_3), 4.87 (1H, ddd, J = 9.6, 8.4, 4.6 Hz, C_1-H). *Anal.* Calcd for $C_{11}H_{16}N_2O_4$: C, 54.99; H, 6.71; N, 11.66. Found: C, 55.02; H, 6.90; N, 11.54.

***trans*-2-(*p*-Methoxybenzyloxy)-1-cyclohexanol (6)** PMB alcohol (1.80 g, 13 mmol) was added to a solution of cyclohexene oxide (982 mg, 10 mmol) in benzene (15 ml) at 0 °C, then boron trifluoride diethyl ether complex (10 drops) was added to the resulting mixture. The whole was stirred at room temperature for 9 h, then poured into H_2O (30 ml), and extracted with EtOAc (3 × 20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 3 : 1) to give **6** (1.66 g, 70%) as a colorless oil. IR (CCl_4) cm^{-1}: 3630, 3580—3300. ^{1}H-NMR (60 MHz, $CDCl_3$) δ: 0.75—2.4 (8H, m, 4 × CH_2), 2.68 (1H, br s, OH), 2.9—3.6 (2H, m, C_1-, C_2-H), 3.58 (3H, s, OCH_3), 4.31, 4.62 (1H each, ABq, J = 11.0 Hz, CH_2Ar), 6.80 (2H, d, J = 9.0 Hz, Ar-H), 7.20 (2H, d, J = 9.0 Hz, Ar-H). *Anal.* Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.42; H, 8.88. Exact MS *m/z*: 236.1402 (Calcd for $C_{14}H_{20}O_3$: 236.1403).

***trans*-2-(*p*-Methoxybenzyloxy)cyclohex-1-yl Diazoacetoacetate (1b)** According to a procedure similar to that described for the preparation of **1a**, **6** (840 mg, 3.56 mmol) was treated with diketene (393 mg, 3.92 mmol) and triethylamine (36 mg, 0.36 mmol) to give the corresponding acetoacetate (880 mg, 77%). Treatment of the acetoacetate (540 mg, 1.61 mmol) with *p*-toluenesulfonyl azide (349 mg, 1.77 mmol) and triethylamine (326 mg, 3.22 mmol) gave **1b** (462 mg, 83%) as a colorless oil. IR (CCl_4) cm^{-1}: 2140 ($C=N_2$), 1720, 1660, 1615, 1510. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.2—1.5 (4H, m, 2 × CH_2), 1.65—1.8 (2H, m, CH_2), 2.0—2.2 (2H, m, CH_2), 2.46 (3H, s, CH_3CO), 3.35 (1H, ddd, J = 9.9, 8.5, 4.4 Hz, C_2-H), 3.80 (3H, s, OCH_3), 4.40, 4.59 (1H each, ABq, J = 11.8 Hz, CH_2Ar), 4.93 (1H, ddd, J = 9.9, 8.7, 4.7 Hz, C_1-H), 6.85 (2H, d, J = 8.8 Hz, Ar-H), 7.21 (2H, d, J = 8.8 Hz, Ar-H). Exact FAB-MS *m/z*: 347.1596 (Calcd for $C_{18}H_{22}N_2O_5 + H^+$: 347.1607).

***trans*-1-(*tert*-Butyldimethylsilyloxy)-2-(*p*-methoxybenzyloxy)cyclohexane (7)** *tert*-Butyldimethylchlorosilane (787 mg, 5.23 mmol) and imidazole (646 mg, 9.5 mmol) were added to a solution of **6** (1.12 g, 4.75 mmol) in dimethylformamide (DMF) (10 ml) at room temperature. The mixture was stirred for 14 h, then poured into H_2O (30 ml), and extracted with Et_2O (3 × 20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 50 : 1) to give **7** (1.31 g, 79%) as a colorless oil. IR (CCl_4) cm^{-1}: 1610, 1510. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.05 (6H, s, 2 × $SiCH_3$), 0.90 (9H, s, *tert*-Bu), 1.15—1.4 (4H, m, 2 × CH_2), 1.55—1.7 (2H, m, CH_2), 1.8—2.0 (2H, m, CH_2), 3.18 (1H, ddd, J = 8.8, 7.3, 3.9 Hz, C_1- or C_2-H), 3.57 (1H, ddd, J = 8.6, 7.2, 4.1 Hz, C_1- or C_2-H), 3.80 (3H, s, OCH_3), 4.55 (2H, s, CH_2Ar), 6.86 (2H, d, J = 8.7 Hz, Ar-H), 7.28 (2H, d, J = 8.7 Hz, Ar-H). *Anal.* Calcd for $C_{20}H_{34}O_3Si$: C, 68.52; H, 9.78. Found: C, 68.74; H, 9.91.

***trans*-2-(*tert*-Butyldimethylsilyloxy)-1-cyclohexanol (8)** DDQ (1.17 g, 5.04 mmol) was added to a mixture of **7** (967 mg, 2.76 mmol) in CH_2Cl_2 (10 ml) and H_2O (1 ml) at room temperature. The mixture was stirred for 1 h, then diluted with CH_2Cl_2 (30 ml), dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 20 : 1) to give **8** (569 mg, 89%) as a colorless oil. IR (CCl_4) cm^{-1}: 3500—3700. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.09 (3H, s, $SiCH_3$), 0.10 (3H, s, $SiCH_3$), 0.91 (9H, s, *tert*-Bu), 1.2—1.35 (4H, m, 2 × CH_2), 1.6—1.75 (2H, m, CH_2), 1.8—2.1 (2H, m, CH_2), 2.3—2.55 (1H, br, OH), 3.3—3.4 (2H, m, C_1-H, C_2-H). Exact FAB-MS *m/z*: 231.1797 (Calcd for $C_{12}H_{26}O_2Si + H^+$: 231.1780).

***trans*-2-(*tert*-Butyldimethylsilyloxy)cyclohex-1-yl Diazoacetoacetate (1c)** According to a procedure similar to that described for the preparation of **1a**, **8** (512 mg, 2.22 mmol) was treated with diketene (267 mg, 2.67 mmol) and triethylamine (449 mg, 4.44 mmol) to give the corresponding acetoacetate (674 mg, 97%). Treatment of the acetoacetate (674 mg, 2.14 mmol) with *p*-toluenesulfonyl azide (633 mg, 3.21 mmol) and triethylamine (650 mg, 6.42 mmol) gave **1c** (610 mg, 84%) as a colorless oil. IR (CCl_4) cm^{-1}: 2130 ($C=N_2$), 1720, 1660. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.03 (3H, s, $SiCH_3$), 0.05 (3H, s, $SiCH_3$), 0.86 (9H, s, *tert*-Bu), 1.2—1.5 (4H, m, 2 × CH_2), 1.6—1.75 (2H, m, CH_2), 1.8—1.95 (1H, m, one of CH_2), 1.95—2.05 (1H, m, one of CH_2), 2.49 (3H, s, CH_3CO), 3.61 (1H, ddd, J = 9.2, 8.0, 4.3 Hz, C_2-H), 4.84 (1H, ddd, J = 9.5, 8.1, 4.4 Hz, C_1-H). *Anal.* Calcd for $C_{16}H_{28}N_2O_4Si$: C, 56.44; H, 8.29; N, 8.23. Found: C, 56.62; H, 8.18; N, 8.41.

***cis*-1-(*tert*-Butyldimethylsilyloxy)-2-(*p*-methoxybenzyloxy)cyclohexane (9)** *p*-Methoxybenzaldehyde dimethylacetal (1.09 g, 6 mmol) and anhydrous p-toluenesulfonic acid (34 mg, 0.2 mmol) were added to a solution of *cis*-1,2-cyclohexanediol (232 mg, 1 mmol) in toluene (10 ml) at room temperature under a nitrogen atmosphere. The mixture was refluxed for 1h, then recooled to 0 °C. DIBAL-H (0.95 M in hexane, 10.5 ml, 10 mmol) was added to the cooled solution. The mixture was stirred at the same temperature for 1.5 h, then methanol (2 ml) and a saturated ammonium chloride solution (2 ml) were added to the mixture. The resulting mixture was stirred for 1 h, then diluted with Et_2O (30 ml), dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 5 : 1) to give *cis*-2-(*p*-methoxybenzyloxy)-1-cyclohexanol (405 mg, 86%) as a colorless oil. According to a procedure similar to that described for the preparation of **7**, **9** (378 mg, 74%) was obtained from the alcohol (346 mg, 1.46 mmol), *tert*-butyldimethylchlorosilane (332 mg, 2.20 mmol), and imidazole (199 mg, 2.96 mmol) as a colorless oil. IR (CCl_4) cm^{-1}: 1610, 1510. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.04 (3H, s, $SiCH_3$), 0.05 (3H, s, $SiCH_3$), 0.89 (9H, s, *tert*-Bu), 1.15—1.9 (8H, m, $4\times CH_2$), 3.33 (1H, dt, $J=8.3$, 2.8 Hz, C_1 or C_2-H), 3.78 (3H, s, OCH_3), 3.85—3.95 (1H, m, C_1 or C_2-H), 4.47, 4.58 (1H each, ABq, $J=11.8$ Hz, CH_2Ar), 6.85 (2H, d, $J=8.7$ Hz, Ar-H), 7.27 (2H, d, $J=8.7$ Hz, Ar-H). *Anal.* Calcd for $C_{20}H_{34}O_3Si$: C, 68.52; H, 9.78. Found: C, 68.98; H, 9.99.

***cis*-2-(*tert*-Butyldimethylsilyloxy)cyclohex-1-yl Diazoacetoacetate (1d)** According to a procedure similar to that described for the preparation of **8**, **9** (345 mg, 0.99 mmol) was treated with DDQ (269 mg, 1.18 mmol) to give *cis*-2-(*tert*-butyldimethylsilyloxy)-1-cyclohexanol (210 mg, 92%). Following a procedure similar to that described for the preparation of **1a**, the alcohol (174 mg, 0.76 mmol) was allowed to react with diketene (91 mg, 0.99 mmol) and triethylamine (153 mg, 1.51 mmol) to give the corresponding acetoacetate (209 mg, 88%), which was treated with *p*-toluenesulfonyl azide (197 mg, 1.0 mmol) and triethylamine (202 mg, 2.0 mmol) to afford **1d** (210 mg, 93%) as a colorless oil. IR (CCl_4) cm^{-1}: 2130 ($C=N_2$), 1710, 1660. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.00 (3H, s, $SiCH_3$), 0.03 (3H, s, $SiCH_3$), 0.86 (9H, s, *tert*-Bu), 1.2—1.45 (2H, m, CH_2), 1.5—2.0 (6H, m, $3\times CH_2$), 2.47 (3H, s, CH_3CO), 3.94 (1H, dt, $J=6.6$, 2.7 Hz, C_2-H), 4.95 (1H, td, $J=8.7$, 2.7 Hz, C_1-H). *Anal.* Calcd for $C_{16}H_{28}N_2O_4Si$: C, 56.44; H, 8.29; N, 8.23. Found: C, 56.52; H, 8.41; N, 8.45.

3-(*p*-Methoxybenzyloxy)cyclohexene (11) 2-Cyclohexen-1-ol (980 mg, 10 mmol) was added to a suspension of sodium hydride (60% dispersion in mineral oil, 1.45 g, 36 mmol) in THF (18 ml) and DMF (6 ml) at 0 °C under a nitrogen atmosphere. The mixture was vigorously stirred for 30 min, then PMB chloride (5.16 g, 33 mmol) and tetrabutylammonium iodide (369 mg, 1 mmol) were added at room temperature. The resulting mixture was stirred for 5 h, then poured onto ice (30 ml). The mixture was extracted with Et_2O (3×20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 50 : 1) to give **11** (1.89 g, 86%) as a colorless oil. IR (CCl_4) cm^{-1}: 1605, 1585, 1505. ^1H-NMR (60 MHz, $CDCl_3$) δ: 1.4—2.3 (6H, m, $3\times CH_2$), 3.78 (3H, s, OCH_3), 3.6—4.1 (1H, m, C_1-H), 4.50 (2H, s, CH_2Ar), 5.6—5.9 (2H, m, C_2-, C_3-H), 6.83 (2H, d, $J=8$ Hz, Ar-H), 7.27 (2H, d, $J=8$ Hz, Ar-H). *Anal.* Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 77.24; H, 8.34.

(1*R,2*R**,3*R**)-3-(*p*-Methoxybenzyloxy)-1,2-cyclohexanediol (12)** Osmium tetroxide (a 4% aqueous solution, 0.7 ml, 0.16 mmol) was added to a solution of **11** (1.39 g, 6.4 mmol) and NMO (a 50% aqueous solution, 2.2 ml, 9.7 mmol) in THF (25 ml) at room temperature. The mixture was stirred for 5 h, then diluted with water (30 ml), and extracted with Et_2O (3×20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–EtOAc, 1 : 1) to give **12** (1.27 g, 79%) as a colorless oil. IR (CCl_4) cm^{-1}: 3500—3700, 1610, 1510. ^1H-NMR (300 MHz, $CDCl_3$) δ: 1.15—1.3 (2H, m, CH_2), 1.35—1.75 (2H, m, CH_2), 1.8—2.1 (2H, m, CH_2), 2.71 (1H, br s, OH), 3.01 (1H, br s, OH), 3.49 (1H, dd, $J=8.6$, 2.9 Hz, $C\underline{H}OH$), 3.60 (1H, ddd, $J=9.7$, 8.8, 4.1 Hz, C_3-H), 3.79 (3H, s, OCH_3), 4.0—4.1 (1H, m, $C\underline{H}OH$), 4.38, 4.59 (1H each, ABq, $J=11.2$ Hz, CH_2Ar), 6.87 (2H, d, $J=8.5$ Hz, Ar-H), 7.26 (2H, d, $J=8.5$ Hz, Ar-H). *Anal.* Calcd for $C_{14}H_{20}O_4$: C, 66.65; H, 7.99. Found: C, 66.95; H, 8.28.

(1*R,2*R**,3*R**)-1-Benzyloxy-2-(*tert*-butyldimethylsilyloxy)-3-(*p*-methoxybenzyloxy)cyclohexane (13)** The procedure was essentially the same as that used for the preparation of **9**. Compound **12** (252 mg, 1 mmol) was allowed to react with benzaldehyde dimethylacetal (0.3 ml, 2 mmol) and *p*-toluenesulfonic acid (2 mg, 0.01 mmol) in toluene (5 ml) at room temperature for 5 h under a nitrogen atmosphere. The crude mixture was treated with DIBAL-H (1.5 M in toluene, 3.3 ml, 5 mmol) at 0 °C for 1 h. Work-up gave (1*R**,2*R**,6*R**)-2-benzyloxy-6-(*p*-methoxybenzyloxy)-1-cyclohexanol (257 mg, 75%) as a colorless oil. The resulting alcohol (324 mg, 0.95 mmol) was then treated with *tert*-butyldimethylchlorosilane (429 mg, 2.85 mmol) and imidazole (258 mg, 3.8 mmol) to give **13** (331 mg, 76%) as a colorless oil. IR (CCl_4) cm^{-1}: 1615, 1510. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.04 (3H, s, $SiCH_3$), 0.88 (9H, s, *tert*-Bu), 1.4—1.55 (4H, m, $2\times CH_2$), 1.7—1.8 (2H, m, CH_2), 3.5—3.65 (2H, m, C_1-, C_3-H), 3.79 (3H, s, OCH_3), 3.85—3.9 (1H, m, C_2-H), 4.41, 4.50 (1H each, ABq, $J=11.5$ Hz, CH_2Ar), 4.53, 4.59 (1H each, ABq, $J=12.2$ Hz, CH_2Ar), 6.86 (2H, d, $J=8.4$ Hz, Ar-H), 7.23 (2H, d, $J=8.4$ Hz, Ar-H), 7.25—7.4 (5H, m, Ar-H). *Anal.* Calcd for $C_{27}H_{40}O_4Si$: C, 71.01; H, 8.83. Found: C, 70.78; H, 9.00.

(1*R,2*R**,3*R**)-3-Benzyloxy-2-(*tert*-butyldimethylsilyloxy)cyclohex-1-yl Diazoacetoacetate (1e)** According to a procedure similar to that described for the preparation of **8**, (1*R**,2*R**,3*R**)-3-benzyloxy-2-(*tert*-butyldimethylsilyloxy)-1-cyclohexanol (182 mg, 75%) was obtained from **13** (331 mg, 0.72 mmol) and DDQ (197 mg, 0.87 mmol). Following a procedure similar to that described for the preparation of **1a**, the resulting alcohol (182 mg, 0.54 mmol) was allowed to react with diketene (65 mg, 0.65 mmol) and triethylamine (109 mg, 1.08 mmol) to give the corresponding acetoacetate (127 mg, 56%), which was then treated with *p*-toluenesulfonyl azide (71 mg, 0.36 mmol) and triethylamine (61 mg, 0.6 mmol) to afford **1e** (110 mg, 83%) as a colorless oil. IR (CCl_4) cm^{-1}: 2130 ($C=N_2$), 1720, 1660. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.08 (3H, s, $SiCH_3$), 0.90 (9H, s, *tert*-Bu), 1.4—2.0 (6H, m, $3\times CH_2$), 2.46 (3H, s, CH_3CO), 3.57 (1H, br d, $J=7.2$ Hz, C_3-H), 3.82 (1H, dd, $J=7.0$, 2.0 Hz, C_2-H), 4.57, 4.64 (1H each, ABq, $J=12.1$ Hz, CH_2Ar), 5.20 (1H, td, $J=6.7$, 3.8 Hz, C_1-H), 7.2—7.4 (5H, m, Ar-H). *Anal.* Calcd for $C_{23}H_{34}N_2O_5Si$: C, 61.85; H, 7.67; N, 6.27. Found: C, 62.04; H, 7.77; N, 6.57.

(1*R,2*R**,3*R**)-3-Benzyloxy-1,2-cyclohexanediol (15)** According to a procedure similar to that described for the preparation of **12**, **15** (1.32 g, 79%) was obtained from **14**[8)] (1.41 g, 7.5 mmol), osmium tetroxide (a 4% aqueous solution, 0.82 ml, 0.19 mmol), and NMO (a 50% aqueous solution, 2.7 ml, 11.5 mmol) as a colorless oil. IR (CCl_4) cm^{-1}: 3500—3700. ^1H-NMR (300 MHz, $CDCl_3$) δ: 1.2—1.8 (4H, m, $2\times CH_2$), 1.8—2.15 (2H, m, CH_2), 2.57 (1H, br s, OH), 2.92 (1H, br s, OH), 3.52 (1H, dd, $J=8.6$, 3.0 Hz, $C\underline{H}OH$), 3.63 (1H, ddd, $J=9.9$, 8.6, 4.0 Hz, C_3-H), 4.08 (1H, dd, $J=6.9$, 3.0 Hz, $C\underline{H}OH$), 4.45, 4.68 (1H each, ABq, $J=11.6$ Hz, CH_2Ar), 7.2—7.4 (5H, m, Ar-H). Exact FAB-MS *m/z*: 245.1161 (Calcd for $C_{13}H_{18}O_3+Na^+$: 245.1153).

(1*R,2*S**,3*R**)-1-Benzyloxy-2-(*tert*-butyldimethylsilyloxy)-3-(*p*-methoxybenzyloxy)cyclohexane (16)** According to a procedure similar to that described for the preparation of **9**, **15** (222 mg, 1 mmol) was treated with *p*-methoxybenzaldehyde dimethylacetal (364 mg, 2 mmol) and *p*-toluenesulfonic acid (2 mg, 0.01 mmol), and then DIBAL-H (0.98 M in hexane, 5.1 ml, 5 mmol) to give crude (1*S**,2*R**,6*R**)-2-benzyloxy-6-(*p*-methoxybenzyloxy)-1-cyclohexanol, which was treated with *tert*-butyldimethylchlorosilane (193 mg, 1.28 mmol) and imidazole (116 mg, 1.7 mmol) to afford **16** (315 mg, 69%) as a colorless oil. IR (CCl_4) cm^{-1}: 1615, 1510. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.04 (3H, s, $SiCH_3$), 0.89 (9H, s, *tert*-Bu), 1.4—1.6 (4H, m, $2\times CH_2$), 1.65—1.85 (2H, m, CH_2), 3.55—3.65 (1H, m, C_1-H), 3.63 (1H, dt, $J=8.9$, 2.6 Hz, C_3-H), 3.78 (3H, s, OCH_3), 3.85—3.9 (1H, m, C_2-H), 4.47, 4.52 (1H each, ABq, $J=11.9$ Hz, CH_2Ar), 4.48, 4.58 (1H each, ABq, $J=12.0$ Hz, CH_2Ar), 6.85 (2H, d, $J=8.5$ Hz, Ar-H), 7.27 (2H, d, $J=8.5$ Hz, Ar-H), 7.3—7.35 (5H, m, Ar-H). Exact FAB-MS *m/z*: 457.2743 (Calcd for $C_{27}H_{40}O_4Si+H^+$: 457.2774).

(1*R,2*S**,3*R**)-3-Benzyloxy-2-(*tert*-butyldimethylsilyloxy)cyclohex-1-yl Diazoacetoacetate (1f)** According to a procedure similar to that described for the preparation of **8**, (1*R**,2*S**,3*R**)-3-benzyloxy-2-(*tert*-butyldimethylsilyloxy)-1-cyclohexanol (90 mg, 74%) was obtained from **16** (165 mg, 0.36 mmol) and DDQ (98 mg, 0.43 mmol). Following a procedure similar to that described for the preparation of **1a**, the resulting alcohol (35 mg, 0.1 mmol) was allowed to react with diketene (120 mg, 1.2 mmol) and triethylamine (20 mg, 0.2 mmol) to give the corresponding acetoacetate (42 mg, quant.), which was treated with *p*-toluenesulfonyl azide (21 mg, 0.11 mmol) and triethylamine (20 mg, 0.2 mmol) to afford **1f** (44 mg, quant) as a colorless oil. IR (CCl_4) cm^{-1}: 2130 ($C=N_2$), 1710, 1660. ^1H-NMR (300 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.03 (3H, s, $SiCH_3$), 0.89 (9H, s, *tert*-Bu), 1.4—1.9 (6H, m, $3\times CH_2$), 2.50 (3H, s, CH_3CO), 3.45—3.55 (1H, m, C_3-H), 3.98 (1H, dd, $J=5.4$, 2.5 Hz, C_2-H), 4.58, 4.63 (1H each, ABq, $J=12.0$ Hz, CH_2Ar), 5.24 (1H, dt, $J=9.2$, 3.0 Hz, C_1-H), 7.2—7.4 (5H, m, Ar-H). Exact FAB-MS *m/z*: 447.2289 (Calcd for $C_{23}H_{34}N_2O_5Si+H^+$: 447.2315).

(1*R,2*S**,3*R**)-3-Benzyloxy-2-(*tert*-butyldimethylsilyloxy)cyclohex-1-yl Ethyl Diazomalonate (17)** Ethyl malonyl chloride (0.14 ml, 1.1 mmol) and triethylamine (0.17 ml, 1.2 mmol) were added to a solution of (1*R**,2*S**,3*R**)-3-benzyloxy-2-(*tert*-butyldimethylsilyloxy)-1-cyclohexanol (337 mg, 1 mmol) in Et_2O (15 ml) at 0 °C. The mixture was stirred at 0 °C for 1.5 h, then poured into H_2O (30 ml) and extracted with Et_2O (3×20 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (hexane–Et_2O, 7 : 1) to give the corresponding malonate (233 mg, 52%) as a colorless oil. The resulting malonate (100 mg, 0.22 mmol) was dissolved in CH_3CN (7 ml), and then 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU)

(0.05 ml, 0.33 mmol) and *p*-toluenesulfonyl azide (51 mg, 0.26 mmol) were added to this solution at room temperature. The mixture was stirred for 17 h, then poured into H_2O (20 ml), and extracted with Et_2O (3 × 10 ml). The extract was washed with brine, dried ($MgSO_4$), and concentrated. The residue was chromatographed on silica gel (benzene–acetone, 70 : 1) to give **17** (90 mg, 86%) as a colorless oil. IR (CCl_4) cm^{-1}: 2130 ($C=N_2$), 1760, 1730, 1690. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.02 (3H, s, $SiCH_3$), 0.87 (9H, s, *tert*-Bu), 1.45—1.9 (6H, m, $3 \times CH_2$), 1.32 (3H, t, $J=7.1$ Hz, CH_3), 3.48—3.55 (1H, m, C_3-H), 3.93—4.0 (1H, m, C_2-H), 4.31 (2H, qd, $J=7.1$, 1.3 Hz, OCH_2), 4.58 (2H, s, CH_2Ar), 5.26 (1H, dt, $J=9.0$, 3.0 Hz, C_1-H), 7.2—7.4 (5H, m, Ar-H). Exact FAB-MS *m*/*z*: 477.2407 (Calcd for $C_{24}H_{36}N_2O_6Si+H^+$: 477.2436).

General Procedure for the Intramolecular C–H Insertion Reaction of Diazo Compounds 1a—1f, and 17 A solution of the diazo compound (0.3 mmol) in benzene (20 ml) was added to a solution of 1 mol% of $Rh_2(OAc)_4$ in refluxing benzene (20 ml) *via* a syringe pump during 4—6 h. After evaporation of the solvent, the crude material was chromatographed on silica gel.

The Intramolecular C–H Insertion Reaction of 1b Following the general procedure, **1b** (126 mg, 0.36 mmol) was treated with $Rh_2(OAc)_4$ (1.5 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 7 : 1) to give a mixture of two diastereoisomers of 3-acetyl-7-(*p*-methoxybenzyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (**2b**) (5 mg, 4%) as a colorless oil. IR (CCl_4) cm^{-1}: 1780, 1720, 1620, 1505. ^{1}H-NMR (300 MHz, $CDCl_3$) for the major isomer δ: 1.2—1.75 (5H, m), 1.8—1.95 (1H, m), 2.42 (3H, s, CH_3CO), 3.1—3.25 (1H, m, C_{3a}-H), 3.41 (1H, d, $J=9.0$ Hz, C_3-H), 3.45 (1H, ddd, $J=9.3$, 6.6, 3.9 Hz, C_7-H), 3.81 (3H, s, OCH_3), 4.43 (1H, t, $J=6.7$ Hz, C_{7a}-H), 4.56, 4.60 (1H each, ABq, $J=11.5$ Hz, CH_2Ar), 6.88 (2H, d, $J=8.7$ Hz, Ar-H), 7.28 (2H, d, $J=9.0$ Hz, Ar-H). Exact MS *m*/*z*: 318.1477 (Calcd for $C_{18}H_{22}O_5$: 318.1476).

The Intramolecular C–H Insertion Reaction of 1c Following the general procedure, **1c** (155 mg, 0.46 mmol) was treated with $Rh_2(OAc)_4$ (2 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 20 : 1). The first fraction gave (4*S**,5*R**)-3-acetyl-5-(*tert*-butyldimethylsilyloxy)-1-oxaspiro[3.5]nonan-2-one (**4c**) (23 mg, 16%, a 4 : 1 mixture of two diastereoisomers) as a colorless oil. IR (CCl_4) cm^{-1}: 1825, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.09 (3H, s, $SiCH_3$), 0.10 (3H, s, $SiCH_3$), 0.87 (1/5 × 9H, s, *tert*-Bu of the minor isomer), 0.90 (4/5 × 9H, s, *tert*-Bu of the major isomer), 1.2—2.1 (6H, m, $3 \times CH_2$), 2.38 (4/5 × 3H, s, CH_3CO of the major isomer), 2.40 (1/5 × 3H, s, CH_3CO of the minor isomer), 3.76 (4/5 × 1H, dd, $J=10.0$, 4.5 Hz, C_5-H of the major isomer), 3.84 (1/5 × 1H, s, C_3-H of the major isomer), 3.91 (1/5 × 1H, dd, $J=11.5$, 5.5 Hz, C_5-H of the minor isomer), 4.61 (4/5 × 1H, s, C_3-H of the major isomer). ^{13}C-NMR (75 MHz, $CDCl_3$) for the major isomer δ: −5.1, −4.7, 18.0, 22.8 (2), 25.6 (3), 30.6, 31.2, 33.1, 62.7, 73.2, 84.3, 164.8, 198.9. Exact FAB-MS *m*/*z*: 313.1839 (Calcd for $C_{16}H_{28}O_4Si+H^+$: 313.1835). The second fraction gave (3*R**,3a*S**,7*R**,7a*R**)-3-acetyl-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (*cis*-**2c**) (31 mg, 22%) as a colorless oil. IR (CCl_4) cm^{-1}: 1780, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.07 (3H, s, $SiCH_3$), 0.10 (3H, s, $SiCH_3$), 0.89 (9H, s, *tert*-Bu), 1.2—1.8 (6H, m, $3 \times CH_2$), 2.41 (3H, s, CH_3CO), 3.1—3.2 (1H, m, C_{3a}-H), 3.41 (1H, d, $J=8.2$ Hz, C_3-H), 3.71 (1H, ddd, $J=8.6$, 5.9, 3.0 Hz, C_7-H), 4.28 (1H, t, $J=6.3$ Hz, C_{7a}-H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: −4.8, −4.4, 18.0, 18.1, 25.2, 25.7 (3), 29.8, 30.7, 36.2, 58.5, 70.3, 82.8, 172.0, 200.2. Exact FAB-MS *m*/*z*: 313.1835 (Calcd for $C_{16}H_{28}O_4Si+H^+$: 313.1835). The third fraction gave (3*S**,3a*R**,7*R**,7a*R**)-3-acetyl-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (*trans*-**2c**) (26 mg, 18%) as a colorless oil. IR (CCl_4) cm^{-1}: 1785, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.09 (3H, s, $SiCH_3$), 0.11 (3H, s, $SiCH_3$), 0.89 (9H, s, *tert*-Bu), 1.1—1.5 (4H, m, $2 \times CH_2$), 1.8—2.1 (2H, m, CH_2), 2.25—2.4 (1H, m, C_{3a}-H), 2.44 (3H, s, CH_3CO), 3.40 (1H, d, $J=12.9$ Hz, C_3-H), 3.69 (1H, dd, $J=10.6$, 8.9 Hz, C_{7a}-H), 3.78 (1H, td, $J=9.0$, 5.0 Hz, C_7-H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: −4.8, −4.6, 18.1, 24.1, 25.7 (3), 26.6, 30.4, 34.4, 43.3, 58.7, 72.2, 86.6, 171.5, 201.3. Exact FAB-MS *m*/*z*: 313.1827 (Calcd for $C_{16}H_{28}O_4Si+H^+$: 313.1835).

The Intramolecular C–H Insertion Reaction of 1d Following the general procedure, **1d** (155 mg, 0.46 mmol) was treated with $Rh_2(OAc)_4$ (2 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 20 : 1). The first fraction gave (4*S**,5*S**)-3-acetyl-5-(*tert*-butyldimethylsilyloxy)-1-oxaspiro[3.5]nonan-2-one (**4d**) (49 mg, 34%, a 2 : 1 mixture of two diastereoisomers) as colorless needles, mp 44.0—47.5 °C (hexane). IR (CCl_4) cm^{-1}: 1830, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.02 (1/3 × 3H, s, $SiCH_3$ of the minor isomer), 0.08 (1/3 × 3H, s, $SiCH_3$ of the minor isomer), 0.09 (2/3 × 3H, s, $SiCH_3$ of the major isomer), 0.10 (2/3 × 3H, s, $SiCH_3$ of the major isomer), 0.85 (1/3 × 9H, s, *tert*-Bu of the minor isomer), 0.89 (2/3 × 9H, s, *tert*-Bu of the major isomer), 1.2—2.1 (6H, m, $3 \times CH_2$), 2.34 (2/3 × 3H, s, CH_3CO of the major isomer), 2.35 (1/3 × 3H, s, CH_3CO of the minor isomer), 3.77 (2/3 × 1H, dd, $J=10.8$, 4.8 Hz, C_5-H of the major isomer), 3.78 (1/3 × 1H, s, C_3-H of the major isomer), 4.19 (1/3 × 1H, dd, $J=11.2$, 4.6 Hz, C_5-H of the minor isomer), 4.53 (4/5 × 1H, s, C_3-H of the major isomer). ^{13}C-NMR (75 MHz, $CDCl_3$) for the major isomer δ: −5.0, −3.8, 18.0, 20.9, 23.6, 25.7 (3), 30.5, 31.4, 31.5, 63.5, 72.3, 84.2, 165.2, 199.0. *Anal.* Calcd for $C_{16}H_{28}O_4Si$: C, 61.50; H, 9.03. Found: C, 61.65; H, 9.20. The second fraction gave (3*R**,3a*S**,7*S**,7a*R**)-3-acetyl-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (*cis*-**2d**) (10 mg, 7%) as a colorless oil. IR (CCl_4) cm^{-1}: 1780, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.07 (3H, s, $SiCH_3$), 0.10 (3H, s, $SiCH_3$), 0.91 (9H, s, *tert*-Bu), 1.2—1.8 (6H, m, $3 \times CH_2$), 2.42 (3H, s, CH_3CO), 3.05—3.15 (1H, m, C_{3a}-H), 3.80 (1H, d, $J=12.3$ Hz, C_3-H), 4.1—4.15 (1H, m, C_7-H), 4.33 (1H, dd, $J=7.4$, 4.1 Hz, C_{7a}-H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: −5.3, −5.2, 13.4, 17.9, 24.2, 25.7 (3), 30.0, 30.2, 35.6, 56.6, 67.5, 76.9, 172.8, 214.2. Exact FAB-MS *m*/*z*: 313.1825 (Calcd for $C_{16}H_{28}O_4Si+H^+$: 313.1835). The third fraction gave (3*S**,3a*R**,7*S**,7a*R**)-3-acetyl-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (*trans*-**2d**) (26 mg, 18%) as colorless plates, mp 89.0—91.0 °C (hexane–EtOAc). IR (CCl_4) cm^{-1}: 1780, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.06 (3H, s, $SiCH_3$), 0.07 (3H, s, $SiCH_3$), 0.88 (9H, s, *tert*-Bu), 1.1—1.5 (4H, m, $2 \times CH_2$), 1.8—2.1 (2H, m, CH_2), 2.39 (3H, s, CH_3CO), 2.98 (1H, qd, $J=11.0$, 4.0 Hz, C_{3a}-H), 3.27 (1H, d, $J=13.0$ Hz, C_3-H), 3.80 (1H, dd, $J=11.1$, 2.1 Hz, C_{7a}-H), 4.3—4.4 (1H, m, C_7-H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ: −5.0, −4.8, 18.1, 20.0, 25.7 (3), 27.8, 30.0, 32.0, 37.5, 59.0, 65.3, 84.4, 172.0, 201.5. *Anal.* Calcd for $C_{16}H_{28}O_4Si$: C, 61.50; H, 9.03. Found: C, 61.46; H, 9.18.

The Intramolecular C–H Insertion Reaction of 1e Following the general procedure, **1e** (73 mg, 0.16 mmol) was treated with $Rh_2(OAc)_4$ (1 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 10 : 1) to give an inseparable 5 : 2 mixture of (3*R**,3a*S**,6*R**,7*R**,7a*R**)- and (3*S**,3a*R**,6*R**,7*R**,7a*R**)-3-acetyl-6-benzyloxy-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-ones (*cis*- and *trans*-**2e**) (51 mg, 75%) as a colorless oil. IR (CCl_4) cm^{-1}: 1780, 1720. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.07 (5/7 × 3H, s, $SiCH_3$ of the major isomer), 0.11 (2/7 × 3H, s, $SiCH_3$ of the minor isomer), 0.12 (5/7 × 3H, s, $SiCH_3$ of the major isomer), 0.14 (2/7 × 3H, s, $SiCH_3$ of the minor isomer), 0.92 (5/7 × 9H, s, *tert*-Bu of the major isomer), 0.93 (2/7 × 9H, s, *tert*-Bu of the minor isomer), 1.2—2.1 (4H, m, $2 \times CH_2$), 2.2—2.4 (2/7 × 1H, m, C_{3a}-H of the minor isomer), 2.41 (5/7 × 3H, s, CH_3CO of the major isomer), 2.44 (2/7 × 3H, s, CH_3CO of the minor isomer), 3.1—3.2 (5/7 × 1H, m, C_{3a}-H of the major isomer), 3.40 (5/7 × 1H, d, $J=8.5$ Hz, C_3-H of the major isomer), 3.42 (2/7 × 1H, d, $J=12.7$ Hz, C_3-H of the minor isomer), 3.63 (5/7 × 1H, dt, $J=6.5$, 2.3 Hz, C_6-H of the major isomer), 3.76 (5/7 × 1H, dd, $J=6.8$, 2.2 Hz, C_7-H of the major isomer), 3.8—3.85 (2/7 × 1H, br, C_7-H of the minor isomer), 4.32 (2/7 × 1H, dd, $J=11.1$, 9.2 Hz, C_{7a}-H of the minor isomer), 4.61 (5/7 × 1H, t, $J=6.8$ Hz, C_{7a}-H of the major isomer), 4.62, 4.83 (2/7 × 1H each, ABq, $J=11.7$ Hz, CH_2Ar of the minor isomer), 4.60, 4.69 (5/7 × 1H each, ABq, $J=12.0$ Hz, CH_2Ar of the major isomer), 7.2—7.4 (5H, m, Ar-H). ^{13}C-NMR (75 MHz, $CDCl_3$) for the major isomer δ: −4.9, −4.8, 18.1, 23.5, 25.7 (3), 29.6, 35.6, 43.7, 58.7, 71.7, 76.5 (2), 82.4, 127.4 (2), 127.5 (2), 128.3, 138.5, 171.9, 200.0. Exact FAB-MS *m*/*z*: 419.2248 (Calcd for $C_{23}H_{34}O_5Si+H^+$: 419.2254).

The Intramolecular C–H Insertion Reaction of 1f Following the general procedure, **1f** (38 mg, 0.085 mmol) was treated with $Rh_2(OAc)_4$ (0.3 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 15 : 1) to give (3*S**,3a*R**,6*R**,7*S**,7a*R**)-3-acetyl-6-benzyloxy-7-(*tert*-butyldimethylsilyloxy)-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-2-one (*trans*-**2f**) (22 mg, 62%) as a colorless oil. IR (CCl_4) cm^{-1}: 1780, 1720. ^{1}H-NMR (270 MHz, $CDCl_3$) δ: 0.01 (3H, s, $SiCH_3$), 0.03 (3H, s, $SiCH_3$), 0.85 (9H, s, *tert*-Bu), 1.4—1.9 (4H, m, $2 \times CH_2$), 2.40 (3H, s, CH_3CO), 2.8—3.0 (1H, m, C_{3a}-H), 3.31 (1H, d, $J=12.9$ Hz, C_3-H), 3.55—3.6 (1H, m, C_6-H), 4.22 (1H, dd, $J=11.2$, 2.0 Hz, C_{7a}-H), 4.26 (1H, dd, $J=5.6$, 2.3 Hz, C_7-H), 4.46, 4.60 (1H each, ABq, $J=11.9$ Hz, CH_2Ar), 7.2—7.4 (5H, m, Ar-H). ^{13}C-NMR (68 MHz, $CDCl_3$) δ: −5.2, −4.9, 18.0, 23.0, 24.4, 25.6 (3), 29.8, 37.0, 58.9, 67.1, 71.2, 78.2, 81.5, 127.5 (2), 127.9, 128.5 (2), 138.0, 171.9, 201.5. Exact FAB-MS *m*/*z*: 419.2251 (Calcd for $C_{23}H_{34}O_5Si+H^+$: 419.2253). When the same reaction was carried out in refluxing toluene, *trans*-**2f** (44 mg, 48%) was obtained from **1f** (100 mg, 0.22 mmol) and $Rh_2(OAc)_4$ (1 mg).

The Intramolecular C–H Insertion Reaction of 17 Following the general procedure, **17** (90 mg, 0.19 mmol) was treated with $Rh_2(OAc)_4$ (0.3 mg) and the crude material was chromatographed on silica gel (hexane–EtOAc, 20 : 1) to give an inseparable 1 : 7 mixture of ethyl (3*R**,3a*S**,6*R**,7*S**,7a*R**)- and (3*S**,3a*R**,6*R**,7*S**,7a*R**)-6-benzyloxy-7-(*tert*-butyldimethylsilyloxy)-2-oxo-2,3,3a,4,5,6,7,7a-octahydrobenzo[*b*]furan-3-carboxylates (*cis*-**18** and *trans*-**18**) (26 mg, 31%) as a colorless oil. IR (CCl_4) cm^{-1}: 1790, 1735. ^{1}H-NMR (300 MHz, $CDCl_3$) for the major isomer δ: 0.02 (3H, s, $SiCH_3$), 0.06 (3H, s, $SiCH_3$), 0.87 (9H, s, *tert*-Bu), 1.5—1.9 (4H, m, $2\times CH_2$), 1.31 (3H, t, $J=7.1$ Hz, CH_3), 2.97 (1H, qd, $J=13.0$, 6.0 Hz, C_{3a}-H), 3.25 (1H, d, $J=13.1$ Hz, C_3-H), 3.6—3.65 (1H, m, C_6-H), 4.2—4.3 (2H, m, C_7- and C_{7a}-H), 4.26 (2H, q, $J=7.1$ Hz, CH_2O), 4.47, 4.60 (1H each, ABq, $J=11.8$ Hz, CH_2Ar), 7.25—7.4 (5H, m, Ar-H). ^{13}C-NMR (75 MHz, $CDCl_3$) for the major isomer δ: −5.2, −4.9, 14.1, 18.0, 22.9, 24.5, 25.6 (3), 39.2, 52.7, 61.8, 67.1, 78.2, 71.4, 81.9, 127.5 (2), 127.9, 128.5 (2), 137.9, 167.6, 171.4. Exact FAB-MS *m/z*: 449.2354 (Calcd for $C_{24}H_{36}O_6Si+H^+$: 449.2360).

References and Notes

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