A Michael Addition and Alkylation Sequence Using Methyl 2-(Trimethylsilyl)-propenoate. Stereoselective Synthesis of α-Silyl Esters

Junji TANAKA,* Shuji KANEMASA,* Yusuke NINOMIYA, and Otohiko TSUGE
Institute of Advanced Material Study, and Department of Molecular Science and Technology, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasugakoen, Kasuga 816
(Received August 28, 1989)

Michael addition of organomagnesiums or -lithiums with methyl 2-(trimethylsilyl)propenoate leads to either 1 : 1 or 1 : 2 adduct anions, depending upon the reaction conditions and the reactivity of donor molecules. The adduct anions, both 1 : 1 and 1 : 2 types, are quenched with alkyl halides or water in a highly stereoselective manner to produce α-silylated esters. A rigid intramolecular chelation working in the adduct anions is partly responsible for the high selectivity.

Methyl 2-(trimethylsilyl)propenoate (**1**) is known as an excellent acceptor in the Michael reactions with organomagnesiums and -lithiums.[1,2] The resulting 1 : 1 adduct anions are reactive as a donor enough to repeat Michael addition to another molecule of **1** forming 1 : 2 adduct anions which are highly stabilized by a rigid intramolecular chelation, especially so in a nonpolar solvent.[3] Predominant formation of the 1 : 1 adduct anions between **1** and the lithium enolates of esters can be achieved in such a nonpolar solvent.[3]

Adduct anions formed in the Michael addition of **1** are the metal enolates of α-silylated esters so that they can be utilized for the one-flask Peterson-olefination procedure by condensation with carbonyl compounds leading to α-alkylated α,β-unsaturated esters.[1-3] Another utilization of the adduct anions in organic synthesis would be the in situ alkylation or protonation leading to α-silylated esters which are rather difficult to prepare by other routes.[4]

In the present article, a stereoselective Michael addition-alkylation (or Michael addition-protonation)[5] sequence using methyl 2-silylpropenoate **1** with organomagnesiums or -lithiums is described in detail.

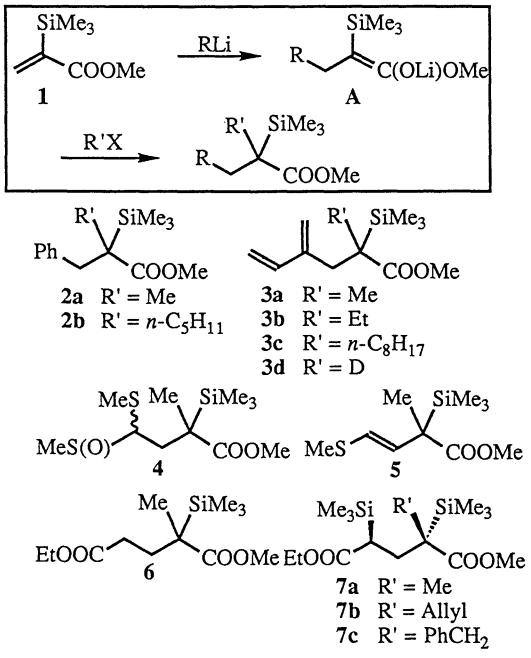
Results and Discussion

The Michael addition of phenyllithium with methyl 2-(trimethylsilyl)propenoate (**1**) has been reported in the preceding paper.[3] Thus, a slightly excess (1.2 equiv) of phenyllithium was allowed to react with **1** at −30 °C in tetrahydrofuran (THF) by employing a rapid mixing method,[3] and the resulting 1 : 1 adduct anion **A** was treated with methyl iodide at room temperature to give methyl 2-methyl-3-phenyl-2-(trimethylsilyl)propanoate (**2a**) in 98% yield (Scheme 1). Use of phenylmagnesium bromide instead of phenyllithium failed to lead to the selective formation of 1 : 1 adduct anion.

Similar Michael addition and alkylation sequences can be carried out by employing other donor molecules such as 2-lithio-1,3-butadiene, methyl lithio(methylsulfinyl)methyl sulfide, and the lithium enolate of ethyl acetate and alkylation reagents such as methyl, ethyl, pentyl, and octyl iodides (Scheme 1). Thus, α-alkyl-α-trimethylsilyl esters **2a,b**, **3a—c**, **4**, and **5** were obtained in good to excellent yields (Table 1, Entries 1—8).

The product **4** derived from the Michael addition using methyl lithio(methylsulfinyl)methyl sulfide was found to be a mixture of diastereomers (Entry 7). This adduct **4** suffered from a ready elimination of the sulfinyl moiety on heating to give β,γ-unsaturated ester **5**.

Interestingly, the Michael-alkylation product **7a** derived from the lithium enolate of ethyl (trimethylsilyl)acetate and methyl iodide was a single diastereomer (Entry 9). Alkylation of the same 1 : 1 adduct anion **A** [R=CH(COOEt)(SiMe$_3$)] with allyl and benzyl bromides, though hexamethylphosphoric triamide (HMPA) was needed to activate the anion **A** in the latter case, was again diastereoselective to give **7b,c** as single isomers (Entries 10, 11). On the other hand, quenching of the same adduct anion **A** with water



Scheme 1.

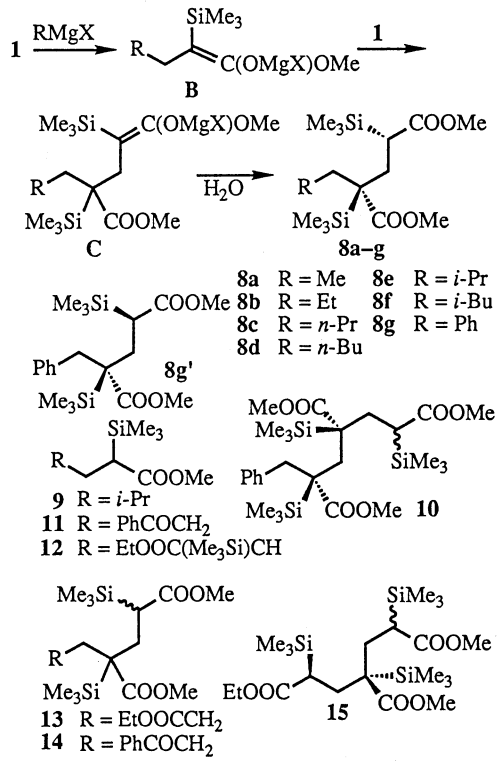
Table 1. Michael Reactions and Subsequent Alkylation of Methyl 2-(Trimethylsilyl)propenoate **1**

Entry	Donor (equiv)	Solvent	Reaction conditions[a]		Alkyl halide	Reaction conditions[b]		Product (yield/%)[c]
			Temp./°C	Time/h		Temp./°C	Time/h	
1	PhLi (1.2)	THF	−30	1	MeI	−30 to rt	0.5+1	**2a** (98)
2	PhLi (1.2)	THF	−30	1	n-$C_5H_{11}I$	−30 to rt	0.5+1	**2b** (62)
3	C_4H_5Li (1.1)[d]	THF	−78	1	MeI	−78 to rt	0.5+1	**3a** (81)
4	C_4H_5Li (1.1)[d]	THF	−78	1	EtI	−78 to rt	0.5+1	**3b** (79)
5	C_4H_5Li (1.1)[d]	THF	−78	1	n-$C_8H_{17}I$	−78 to rt	0.5+1	**3c** (79)
6	C_4H_5Li (1.1)[d]	THF	−78	1	D_2O	−78	5 min	**3d** (90)
7	$C_3H_7OS_2Li$ (1.1)[e]	THF	−78	1	MeI	−78 to rt	0.5+0.5	**4** (79, 7 : 4)[f]
8	CH_2=C(OLi)OEt (2)	EtOEt	−78	1	MeI	−78 to rt	2+12	**6** (65)
9	TMSCH=CH(OLi)OEt (2)	EtOEt	−78	1	MeI	−78 to rt	0.5+1	**7a** (75, single)
10	TMSCH=CH(OLi)OEt (2)	EtOEt	−78	1	CH_2=$CHCH_2Br$	−78 to rt	2+12	**7b** (67, single)
11	TMSCH=CH(OLi)OEt (2)	EtOEt	−78	1	$PhCH_2Br$[g]	−78 to rt	1+16	**7c** (49, single)

a) Conditions for the step of Michael addition. To the solution of an acceptor was added **1** in a period of a few seconds. b) Conditions for the step of alkylation. c) Yield of isolated product based on **1**. d) 2-Lithio-1,3-butadiene generated from 2-(tributylstannyl)-1,3-butadiene and butyllithium. e) Methyl lithio(methylsulfinyl)-methyl sulfide. f) Isomer ratio determined by ^{1}H NMR. g) HMPA (0.5 ml for 1 mmol of **1**) was added in the alkylation step.

produced **7d** as a 5 : 4 mixture of two diastereomers (Entry 12). These stereoselectivity and the structural assignment of the Michael/alkylation products **7a—c** will be discussed below.

As previously reported,[3] when alkyl Grignard reagents were employed as donor molecules in the Michael addition of **1**, the reaction was not terminated at the stage of formation of 1 : 1 adduct anions **B** but led to the selective formation of 1 : 2 adduct anions **C** (Scheme 2, R=alkyl for both **B** and **C**). Isopropylmagnesium bromide was the only exception for the selective 1 : 2 adduct formation, 1 : 2 adduct **8e** having been accompanied by 1 : 1 adduct **9** (Entry 5). It was very surprising to find that the quenching of anions **C** with water took place in an absolutely diastereoselective manner to give **8a—f** as single diastereomers (Table 2, Entries 1—6).



Scheme 2.

A similar Michael reaction between **1** and half an equivalent amount of phenylmagnesium bromide in diethyl ether gave 1 : 2 adduct **8g** also as a single diastereomer (Entry 7), while the identical reaction in THF produced a 3 : 2 mixture of two diastereomers, **8g** and **8g′** (Entry 8), showing the dependence of stereoselectivity upon the nature of solvent. Use of 1/3 equivalent of phenyllithium in THF led to the formation of 1 : 2 adduct **8g** and **8g′** along with 1 : 3 adduct **10**, both as mixtures of two diastereomers (Entries 9, 10). Thus, the nature of the metal atom involved in the 1 : 2 adduct enolates is apparently responsible for the diastereoselectivity in the water quenching reaction.

The 1 : 1 adduct anions between **1** and the metal enolates of esters have a structure of monoenolate of pentanedioate which is common to that of 1 : 2 adduct intermediate **C**, indicating a possibility of diastereoselective water quenching. Thus, the reaction of **1** with two equivalents of the lithium enolate of ethyl (trimethylsilyl)acetate in diethyl ether was carried out. Although the 1 : 1 adduct **12** was obtained in an excellent yield, its diastereoselectivity was poor, a 5 : 4 mixture of two isomers having resulted (Entry 13).[6]

Water quenching of the 1 : 2 adduct anions formed from the reactions of **1** with 1/2 equivalent of the lithium enolates of ethyl acetate and ethyl (trimethylsilyl)acetate in THF produced 1 : 2 adducts **13** and **15**, respectively, again as mixtures of diastereomers (Entries 11 and 14). A similar reaction with the lithium enolate of acetophenone afforded 1 : 1 and 1 : 2 adducts, **11** and **14**, even when 1.5 equivalents of the donor molecule were employed (Entry 12). It is inter-

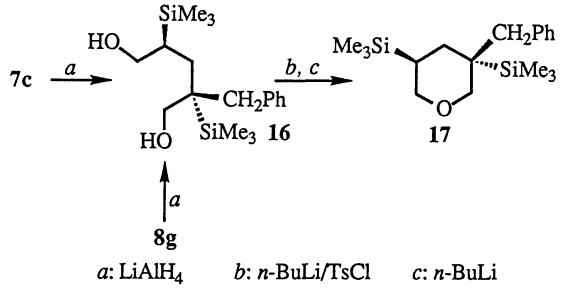
Table 2. Michael Reactions of **1** with Alkyl Grignard Reagents or Other Donor Molecules

Entry	Donor (equiv)	Catalyst	Solvent	Reaction conditions[a]		Product (yield/%)[b]
				Temp./°C	Time/h	
1	MeMgI (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8a** (71)[d]
2	EtMgBr (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8b** (73)[d]
3	*n*-PrMgBr (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8c** (67)[d]
4	*n*-BuMgBr (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8d** (65)[d]
5	*i*-PrMgBr (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8e** (19)[d] **9** (36)
6	*i*-BuMgBr (1)	CuCl (0.5)[c]	EtOEt	−15	1	**8f** (62)[d]
7	PhMgBr (1/2)	None	EtOEt	−15	1	**8g** (87)[d]
8	PhMgBr (1/2)	None	THF	−15	1	**8g**+**8g′** (63, 3:2)[e]
9	PhLi (1/3)	None	THF	−78	1	**8g**+**8g′** (65, 2:3)[e] **10** (17)[f]
10	PhLi (1/3)	None	THF	−78	20	**8g**+**8g′** (37, 2:3)[e] **10** (47, 7:1)[e]
11	CH_2=C(OLi)OEt (1/2)	None	THF	−78	1	**13** (76, 3:2)[g]
12	CH_2=C(OLi)Ph (1.5)	None	THF	−78 to 0	0.5+1	**11** (27) **14** (30, 8:1)[e]
13	TMSCH=C(OLi)OEt (2)	None	EtOEt	−78	1.5	**12** (92, 5:4)[h]
14	TMSCH=C(OLi)OEt(1/2)	None	THF	−78	1	**15** (46, 3:1)[e]

a) Conditions for the step of Michael addition. b) Yield of isolated product based on **1**. c) Mole %. d) Single diastereomer. e) Isomer ratio determined by ^{1}H NMR. f) No isomer ratio was available. g) Isomer ratio determined by ^{13}C NMR. h) Isomer ratio determined by GLC.

esting that diastereomer ratio was much better in the case of **14** (8:1) than that of **13** (3:2). Among four possible diastereomers of **15**, only two were obtained in a 3:1 ratio. The first two asymmetric centers (2- and 4-positions) of **15** must have been constructed stereoselectively because the alkylation of anion **A** [R=CH(SiMe$_3$)COOEt] leading to **7a—c** took place in an absolutely diastereoselective manner as mentioned above. Accordingly, stereostructure of **15** can be tentatively assigned as shown in Scheme 2.

Stereostructures of the diastereoselective 1:1 adducts **7a—c** as well as 1:2 adducts **8a—g** were determined on the basis of the following chemical conversions[7] of **7c** and **8g**. Also informative was the possible mode of stereoselective Michael addition which will be discussed below. Compound **8g**, the product obtained by water quenching of the 1:2 adduct anion **C** (R=Ph, X=Br) derived from **1** and phenylmagnesium bromide, was reduced with lithium aluminum hydride (LAH) to give diol **16**. Treating **16** successively with butyllithium and *p*-toluenesulfonyl chloride and subsequent cyclization of the resulting tosylate produced tetrahydropyran **17** in a total yield of 55% based on **8g** (Scheme 3). Diol **16** was also obtained by the LAH reduction of **7c** which was



Scheme 3.

produced by the diastereoselective benzylation of the 1:1 adduct anion **A** [R=CH(COOEt)(SiMe$_3$)] derived from **1** and the lithium enolate of ethyl (trimethylsilyl)acetate.

Stereostructure of **17** was determined to be 3-benzyl-*r*-3,*t*-5-bis(trimethylsilyl)perhydropyran on the basis of ^{1}H NMR spectrum. The trimethylsilyl group appeared at δ=0.11 was confirmed to attach to 3-position due to a strong NOE with benzyl protons (Fig. 1). This silyl group showed another NOE with a doublet proton at 3.99 which can be assigned to be 2-H$_{eq}$, and no NOE with 2-H$_{ax}$ (3.12). The trimethylsilyl group appeared at −0.09 must occupy the equatorial position regardless of the configuration at 3-position. Therefore, the structure of **17** was assigned.

Thus, high stereoselectivity was observed in the alkylation of the 1:1 adduct of **1** with the lithium enolate of ethyl (trimethylsilyl)acetate and also in the protonation of the 1:2 adduct anions formed from **1** and Grignard reagents in diethyl ether solvent. On the other hand, the adduct anions derived from organolithiums, methyl lithio(methylsulfinyl)methyl sulfide, and lithium enolates of esters were protonated nonstereoselectively.

Michael adduct anions of **1** are the type of metal enolates of esters, and high diastereoselectivity was observed only when an additional ester group was introduced from the donor molecule. Unlike the alkylative quenching, the water quenching was extremely sensitive to the solvation ability of solvent; high selectivity was achieved only when diethyl ether was used as solvent and magnesium enolates as donor molecules. It is likely that a cyclic metal chelation working in the adduct anions would play a central role for the high selectivity, especially so in the alkylating quenching.

A possible stereoselective path leading to **7a—c** and

8a—g is depicted in Fig. 1. The Michael addition of **1** with the lithium enolate of ethyl (trimethylsilyl)acetate forms (*E*)-enolate **E** via approach **D**.[8] This adduct anion **E** is stabilized through the eight-membered chelation where the bulky silyl moiety sits at the equatorial position. Similarly, (*E*)-enolates **G** are formed as 1 : 2 adduct anions from the reaction of **1** with 1 : 1 adduct enolates **F**. The bulkier silyl moiety again exists at the equatorial position. Alkylation of **E** or protonation of **G** occurrs at the outer side of these cyclic intermediates to give **7a—c** or **8a—g** all as single diastereomers.

There are two comparably possible explanations for the observed high stereoselectivity on the water quenching. One explanation is that water quenching of enolates generally takes place with a poor diastereoselectivity because the addition of highly reactive and polar reagents such as water disorders the chelation-ordered system.[9,10] Accordingly, only the rigid magnesium enolates (**G**: Mtl=MgX) generated in less polar diethyl ether could survive on water quenching to be protonated diastereoselectively. The 8 : 1 isomer ratio for **14** (Table 2, Entry 12) is also attributable to a strong chelation of the benzoyl moiety. Water quenching of the 1 : 3 adduct anion derived from phenylmagnesium bromide and three equivalents of **1** provided a 7 : 1 mixture of **10** (Table 2, Entry 10), indicating that the additional ester function would increase the stabilization of chelation [**G**: Mtl=Li, R=$PhCH_2(COOMe)(SiMe_3)C$]. The two

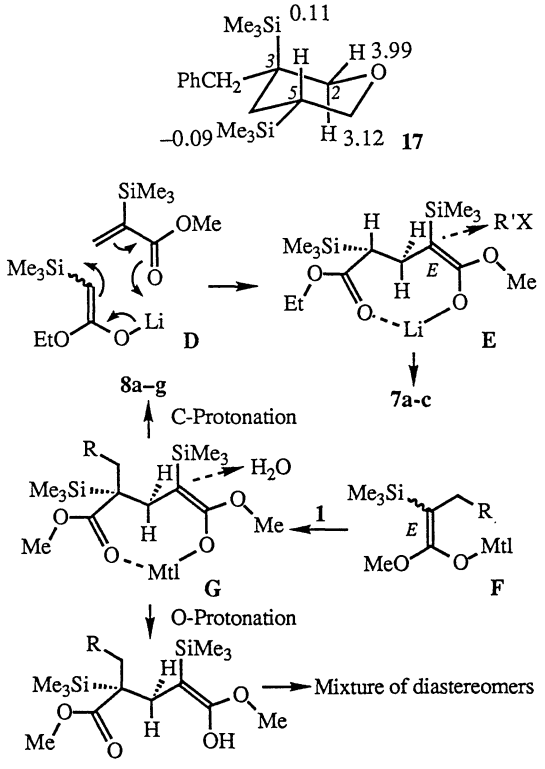


Fig. 1. Stereoselective formation of the Michael addition-alkylation products **7a—c** and the 2 : 1 adducts **8a—g**.

earlier asymmetric centers of **10** and **15** are most likely to have been constructed stereoselectively.

The second explanation is a competition between the *C*-protonation and *O*-protonation, as already discussed by Takano and coworkers.[11] Stereoselectivity of the *C*-protonation depends upon the stability of the chelating intermediate, while the *O*-protonation leads to the formation of enol forms of esters which then undergo nonstereoselective tautomerization producing mixture of two stereoisomers. The magnesium-oxygen bond must be less ionic than the lithium-oxygen bond so that the *C*-protonation becomes a major path in the quenching of magnesium enolates.

In conclusion, a Michael addition and alkylation sequence of methyl 2-(trimethylsilyl)propenoate **1** provides a convenient entry to α-alkylated α-silyl esters which are otherwise difficult to be synthesized. This alkylation takes place in an absolutely diastereoselective fashion. Similarly, the Michael adduct anions of **1** with the magnesium enolates of esters, when formed in a less polar solvent, can be quenched diastereoselectively with water leading to α-silylated esters.

Experimental

General and Materials. For the instruments used for the record of spectral data, see Refs. 2 and 3. Methyl 2-(trimethylsilyl)propenoate (**1**), 1-ethyl 5-methyl 2,4-bis(trimethylsilyl)pentanedioate (**12**), 7-ethyl 1-methyl 4-methoxycarbonyl-2,4-bis(trimethylsilyl)heptanedioate (**13**), and 1-ethyl 7-methyl 4-methoxycarbonyl-2,4,6-tris(trimethylsilyl)heptanedioate (**15**) are all known compounds.[3]

General Procedure for the Michael Reactions and Subsequent Alkylation. As a typical procedure, the reaction of **1** with phenyllithium and quenching with methyl iodide is described as follows: To phenyllithium (1 M in diethyl ether, 3.6 ml, 3.6 mmol; 1 M=1 mol dm^{-3}) in dry THF (5 ml) was added rapidly (in a few seconds) by the aid of a syringe, at −30 °C under nitrogen, the THF (1 ml) solution of **1** (0.474 g, 3 mmol). After 1 h at −30 °C, methyl iodide (0.852 g, 6 mmol) was added. The mixture was stirred at −30 °C for 30 min, at room temperature for 1 h, poured into aqueous ammonium chloride, and extracted with diethyl ether (25 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed on silica gel by using hexane-diethyl ether (19 : 1 v/v) to give **2a** (0.733 g, 98%).

The reaction conditions and results for other combinations of donors and alkyl halides are listed in Table 1.

Methyl 2-Methyl-3-phenyl-2-(trimethylsilyl)propanoate (2a): Colorless prisms (hexane): mp 64.5—66 °C; IR (KBr) 1700, 1250, 1170, 1090, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.10 (9H, s, Me_3Si), 1.01 (3H, s, Me), 2.43, 3.50 (each 1H, J_{gem}=13.5 Hz, $PhCH_2$), 3.60 (3H, s, COOMe), and 7.0—7.1 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−3.87 (q, Me_3Si), 16.15 (q, Me), 38.34 (s, 2-C), 39.16 (t, 3-C), 51.02 (q, COOMe), 126.17, 127.99, 129.63 (each d, Ph), 138.73 (s, Ph), and 176.84 (s, COOMe); MS *m/z* (rel intensity, %) 250 (M^+, 28), 146 (32), 131 (31), 118 (base peak), 117 (35), 116 (21), 91 (38), 89 (36), and 73 (65). Found: C, 67.28; H, 9.05%. Calcd for

$C_{14}H_{22}O_2Si$: C, 67.15; H, 8.86%.

Methyl 2-Benzyl-2-(trimethylsilyl)heptanoate (2b): Purified by silica-gel column chromatography with hexane–diethyl ether (19 : 1 v/v). Colorless liquid; bp 150—152 °C/267 Pa (bulb-to-bulb); IR (neat) 1710, 1450, 1250, 1180, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.09 (9H, s, Me_3Si), 0.7—1.7 (11H, m, n-C_5H_{11}), 2.70, 3.38 (each 1H, d, J_{gem}=14.0 Hz, $PhCH_2$), 3.64 (3H, s, COOMe), and 7.16 (5H, br s, Ph); ^{13}C NMR ($CDCl_3$) δ=−2.24 (q, Me_3Si), 14.03 (q, Me), 22.42, 25.78, 31.67, 32.80, 38.16 (each t, n-C_5H_{11} and $PhCH_2$), 40.03 (s, 2-C), 50.83 (q, COOMe), 126.16, 127.96, 129.82 (each d, Ph), 139.17 (s, Ph), and 176.55 (s, COOMe); MS m/z (rel intensity, %) 306 (M^+, 28), 249 (34), 145 (86), 131 (19), 117 (60), 115 (19), 91 (56), 89 (34), and 73 (base peak). Found: C, 70.73; H, 9.93%. Calcd for $C_{18}H_{30}O_2Si$: C, 70.53; H, 9.86%.

Methyl 2-Methyl-4-methylene-2-trimethylsilyl-5-hexenoate (3a): Purified by silica-gel column chromatography with hexane–diethyl ether (15 : 1 v/v). Colorless liquid; bp 80—82 °C/173 Pa (bulb-to-bulb); IR (neat) 1720, 1250, 1200, 1090, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.08 (9H, s, Me_3Si), 1.12 (3H, s, Me), 2.21, 2.99 (each 1H, d, J_{gem}=14.5 Hz, 3-H), 3.60 (3H, s, COOMe), 4.8—5.3 (4H, m, $=CH_2$), and 6.31 (1H, J_{trans}=17.5 and J_{cis}=11.0 Hz, 5-H); ^{13}C NMR ($CDCl_3$) δ=−3.93 (q, Me_3Si), 16.05 (q, Me), 34.05 (t, 3-C), 36.58 (s, 2-C), 51.08 (q, COOMe), 113.31, 117.01 (each t, $=CH_2$), 139.90 (d, 5-C), 143.49 (s, 4-C), and 177.42 (s, COOMe); MS m/z (rel intensity, %) 226 (M^+, 11), 94 (64), 89 (27), 79 (43), and 73 (base peak). HRMS Found: m/z 226.1385. Calcd for $C_{12}H_{22}O_2Si$: M, 226.1388.

Methyl 2-Ethyl-4-methylene-2-trimethylsilyl-5-hexenoate (3b): Purified by silica-gel column chromatography with hexane–diethyl ether (15 : 1 v/v). Colorless liquid; IR (neat) 1730, 1715, 1255, 1205, 900, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.11 (9H, s, Me_3Si), 0.92 (3H, t, J=7.5 Hz, Et), 1.59, 1.89 (each 1H, dq, J_{gem}=14.0 and J=7.5 Hz, Et), 2.31, 2.87 (each 1H, d, J_{gem}=15.0 Hz, 3-H), 3.58 (3H, s, COOMe), 4.7—5.3 (4H, m, $=CH_2$), and 6.30 (1H, dd, J_{trans}=17.5 and J_{cis}=11.0 Hz, 5-H); ^{13}C NMR ($CDCl_3$) δ=−2.23 (q, Me_3Si), 11.27 (q, Et), 24.42 (t, Et), 33.29 (t, 3-C), 41.04 (s, 2-C), 50.73 (q, COOMe), 112.96, 116.83 (each t, $=CH_2$), 139.97 (d, 5-C), 143.49 (s, 4-C), and 176.89 (COOMe); MS m/z (rel intensity, %) 240 (M^+, 8), 108 (37), 93 (42), 91 (20), 89 (31), 83 (28), 79 (73), and 73 (base peak). HRMS Found: m/z 240.1503. Calcd for $C_{13}H_{24}O_2Si$: M, 240.1544.

Methyl 4-Methylene-2-octyl-2-trimethylsilyl-5-hexenoate (3c): Purified by silica-gel column chromatography with hexane–diethyl ether (15 : 1 v/v). Colorless liquid; IR (neat) 1730, 1710, 1250, 1200, and 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.10 (9H, s, Me_3Si), 0.7—1.8 (17H, m, n-C_8H_{17}), 2.31, 2.87 (each 1H, J_{gem}=15.0 Hz, 3-H), 3.58 (3H, s, COOMe), 4.8—5.3 (4H, m, $=CH_2$), and 6.30 (1H, dd, J_{trans}=17.5 and J_{cis}=11.0 Hz, 5-H); ^{13}C NMR ($CDCl_3$) δ=−2.41 (q, Me_3Si), 13.97 (q, Me), 22.54, 26.18, 29.18, 30.59, 31.76, 33.35 (each t, n-C_8H_{17} and 3-C), 40.51 (s, 2-C), 50.55 (q, COOMe), 112.72, 116.72 (each t, $=CH_2$), 139.94 (d, 5-C), 143.43 (s, 4-C), and 176.71 (s, COOMe); MS m/z (rel intensity, %) 324 (M^+, 4), 225 (14), 121 (26), 94 (21), 93 (45), 91 (21), 89 (32), 79 (24), and 73 (base peak). HRMS Found: m/z 324.2484. Calcd for $C_{19}H_{36}O_2Si$: M, 324.2483.

Methyl 2-Deuterio-4-methylene-2-trimethylsilyl-5-hexenoate (3d): Purified by silica-gel column chromatography with hexane–diethyl ether (15 : 1 v/v). Colorless liquid; bp 70—72 °C/160 Pa (bulb-to-bulb); IR (neat) 1720, 1250, 1205, and 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.12 (9H, s, Me_3Si), 2.30, 2.70 (each 1H, d, J_{gem}=15.5 Hz, 3-H), 3.59 (3H, s, COOMe), 4.9—5.3 (4H, m, $=CH_2$), and 7.33 (1H, dd, J_{trans}=17.5 and J_{cis}=10.5 Hz, 5-H); MS m/z (rel intensity, %) 213 (M^+, 21), 182 (18), 109 (32), 89 (46), 81 (70), 80 (46), and 73 (base peak). HRMS Found: m/z 213.1292. Calcd for $C_{11}H_{19}DO_2Si$: M, 213.1294.

Methyl 2-Methyl-4-methylthio-4-methylsulfinyl-2-(trimethylsilyl)butanoate (4): Obtained as an inseparable 7 : 4 mixture of two diastereomers (^1H NMR), and purified by silica-gel column chromatography with diethyl ether. Colorless liquid; IR (neat) 1715, 1250, 1055, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.08 (9H, s, Me_3Si), 1.22 (3H, s, Me), 2.15 (4/11×3H, s, MeS), 2.21 (7/11×3H, s, MeS), 2.2—2.4 (2H, m, 3-H), 2.58 (7/11×3H, s, MeSO), 2.75 (4/11×3H, s, MeSO), 3.62 (3H, s, COOMe), and 3.70 (1H, m, CH); ^{13}C NMR ($CDCl_3$) δ=−3.99 (q, Me_3Si), 15.26, 16.26 (each q, Me), 26.83, 29.71 (each t, 3-C), 31.35, 33.83, 34.11, 36.64, 51.25 (q, COOMe), 62.06, 64.64 (each d, 4-C), and 177.18 (s, COOMe).

On the attempted purification by vacuum distillation, **4** was quantitatively converted into methyl (*E*)-2-methyl-4-methylthio-2-trimethylsilyl-3-butenoate (**5**): Colorless liquid; bp 125—127 °C/186 Pa (bulb-to-bulb); IR (neat) 1710, 1250, 1215, 990, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00 (9H, s, Me_3Si), 1.32 (3H, s, Me), 2.21 (3H, s, MeS), 3.62 (3H, s, COOMe), 5.72 (1H, d, J_{trans}=15.2 Hz, 4-H), and 5.99 (1H, d, J_{trans}=15.2 Hz, 3-H); ^{13}C NMR ($CDCl_3$)δ=3.99 (q, Me_3Si), 15.21 (q, Me), 43.09 (s, 2-C), 51.37 (q, COOMe), 120.30 (d, 3-C), 127.05 (d, 4-C), and 174.66 (s, COOMe); MS m/z (rel intensity, %) 232 (M^+, 34), 128 (base peak), 113 (21), 99 (29), 85 (50), and 73 (95). HRMS Found: m/z 232.0954. Calcd for $C_{10}H_{20}O_2SSi$: M, 232.0952.

5-Ethyl 1-Methyl 2-Methyl-2-(trimethylsilyl)pentanedioate (6): Purified by silica-gel column chromatography with hexane. Pale yellow liquid; IR (neat) 1730, 1705, 1245, 1170, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00 (9H, s, Me_3Si), 1.12 (3H, s, Me), 1.20 (3H, t, J=7.0 Hz, COOEt), 1.5—1.7 (1H, m, one of 3-H), 2.1—2.4 (3H, m, 3- and 4-H), 3.50 (3H, s, COOMe), and 4.06 (2H, q, J=7.0 Hz, COOEt); ^{13}C NMR ($CDCl_3$) δ=−4.03 (Me_3Si), 14.15 (Me), 16.05 (COOEt); ^{13}C NMR ($CDCl_3$) δ=−4.03 (Me_3Si), 14.15 (Me), 16.05 (COOEt), 28.62, 30.12 (3- and 4-C), 36.27 (2-C), 51.21 (COOMe), 60.30 (COOEt), 173.72, and 176.94 (each COO); MS m/z (rel intensity, %) 260 (M^+, 5), 215 (15), 173 (35), 160 (15), 128 (12), 117 (13), 99 (16), 89 (13), 75 (12), 73 (58), and 69 (base peak). HRMS Found: m/z 260.1441. Calcd for $C_{12}H_{24}O_4Si$: M, 260.1439.

5-Ethyl 1-Methyl 2-Methyl-2,4-bis(trimethylsilyl)pentanedioate (7a): Purified by silica-gel column chromatography with hexane. Colorless liquid; bp 126—127 °C/186 Pa (bulb-to-bulb); IR (neat) 1710, 1250, 1150, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00, 0.01 (each 9H, s, Me_3Si), 1.05 (3H, s, Me), 1.19 (3H, t, J=7.0 Hz, COOEt), 1.74 (1H, d, J_{4-3}=10.3 Hz, 4-H), 1.94 (1H, dd, J_{gem}=14.0 and J_{3-4}=10.3 Hz, one of 3-H), 2.16 (1H, d, J_{gem}=14.0 Hz, the other of 3-H), 3.59 (3H, s, COOMe), 4.01, and 4.07 (each 1H, q, J=7.5 Hz, COOEt); ^{13}C NMR ($CDCl_3$) δ=−3.93, −2.99 (each q, Me_3Si), 14.15 (q, Me), 15.44 (q, COOEt), 29.94 (t, 3-C), 35.34 (d, 4-C), 39.75 (s, 2-C), 51.08 (q, COOMe), 59.71 (t, COOEt), 176.07, and 176.95 (each COO); MS m/z (rel intensity, %) 332 (M^+, 3), 173 (37), 75 (18), and 73 (base peak). HRMS Found: m/z 332.1823. Calcd for $C_{15}H_{32}O_4Si_2$: M, 332.1837.

5-Ethyl 1-Methyl 2-Allyl-2,4-bis(trimethylsilyl)pentanedioate (7b): Purified by silica-gel column chromatogra-

phy with hexane. Pale yellow liquid; IR (neat) 1715, 1260, 1160, and 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ=−0.01, 0.00 (each 9H, s, Me_3Si), 1.14 (3H, t, J=7.0 Hz, COOEt), 1.82 (1H, dd, J_{4-3}=8.6 and 3.2 Hz, 4-H), 2.0—2.1 (2H, m, 3-H), 2.17 (1H, ddt, J_{gem}=15.1, J=6.5, 1.6, and 1.6 Hz, one of allyl), 2.54 (1H, ddt, J_{gem}=15.1, J=6.5, 1.6, and 1.6 Hz, the other of allyl), 3.56 (3H, s, COOMe), 3.95, 4.01 each 1H, dq, J_{gem}=12.3 and J=7.0 Hz, COOEt), 4.88, 5.02 (each 1H, m, =CH_2), and 5.86 (1H, ddt, J_{trans}=16.7, J_{cis}=10.3, and J=6.5 Hz, =CH); ^{13}C NMR ($CDCl_3$) δ=−2.97, −2.49 (each Me_3Si), 14.28 (COOEt), 28.93 (3-C), 35.01 (4-C), 35.50 (Allyl), 44.04 (2-C), 50.91 (COOMe), 59.80 (COOEt), 116.67 (=CH_2), 136.58 (=CH), 175.85, and 176.16 (each COO); MS m/z (rel intensity, %) 358 (M^+, 6), 233 (11), 199 (16), 185 (25), 173 (16), 147 (16), 95 (41), 75 (19), and 73 (base peak). HRMS Found: m/z 358.1997. Calcd for $C_{17}H_{34}O_4Si_2$: M, 358.1994.

5-Ethyl 1-Methyl 2-Benzyl-2,4-bis(trimethylsilyl)pentanedioate (7c): Purified by silica-gel column chromatography with hexane. Colorless liquid; IR (neat) 1710, 1440, 1250, 1150, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=−0.05, 0.03 (each 9H, s, Me_3Si), 1.15 (3H, t, J=7.0 Hz, COOEt), 2.02 (1H, d, J_{gem}=14.5 Hz, one of 3-H), 2.08 (1H, d, J_{4-3}=10.5 Hz, 4-H), 2.35 (1H, dd, J_{gem}=14.5 and J_{3-4}=10.5 Hz, the other of 3-H), 2.92, 3.15 (each 1H, d, J_{gem}=14.0 Hz, $PhCH_2$), 3.69 (3H, s, COOMe), 3.91, 4.00 (each 1H, dq, J_{gem}=12.0 and J=7.0 Hz, COOEt), and 7.1—7.3 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−2.60, −1.91 (each Me_3Si), 14.51 (COOEt), 30.85 (3-C), 34.75, 37.52 (4-C and $PhCH_2$), 44.89 (2-C), 51.82 (COOMe), 60.01 (COOEt), 126.38, 128.18, 130.70, 139.76 (each Ph), 176.03, and 177.05 (each COO); MS m/z (rel intensity, %) 408 (M^+, 62), 377 (28), 363 (22), 249 (48), 235 (78), 232 (48), 173 (25), 145 (base peak), 131 (30), 117 (33), and 73 (50). HRMS Found: m/z 408.2194. Calcd for $C_{21}H_{36}O_4Si$: M, 408.2235.

General Procedure for the Michael Reactions between 1 and Grignard Reagents Leading to 8a—g. As a typical procedure, the reaction of **1** with methylmagnesium iodide is presented as follows: Copper(I) chloride (1.5 mg) was added at −15 °C under nitrogen to the freshly prepared solution of methylmagnesium iodide (3.3 mmol) in dry diethyl ether (5 ml). After 30 min, **1** (0.474 g, 3 mmol) in diethyl ether (1 ml) was added. The mixture was stirred at −15 °C for 1 h, poured into saturated aqueous ammonium chloride, and extracted with diethyl ether (20 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was subjected to vacuum distillation on a Kugelrohr distilling apparatus to give **8a** (0.707 g, 71%).

Other reactions were carried out under the reaction conditions listed in Table 2 where the results are also summarized.

Dimethyl 2-Ethyl-2,4-bis(trimethylsilyl)pentanedioate (8a): Colorless liquid; bp 240 °C/400 Pa (bulb-to-bulb); IR (neat) 1715, 1250, 1155, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00, 0.03 (each 9H, s, Me_3Si), 0.86 (3H, t, J=7.3 Hz, Et), 1.39 (1H, dq, J_{gem}=14.5 and J=7.3 Hz, one of Et), 1.6—2.1 (4H, m, 3-, 4-H, and the other of Et), 3.50, and 3.51 (each 3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−3.01, −2.30 (each q, Me_3Si), 11.12 (q, Et), 28.65 (t, Et), 30.94 (t, 3-C), 34.94 (d, 4-C), 44.74 (s, 2-C), 50.94, 51.06 (each q, COOMe), and 176.89 (COOMe); MS m/z (rel intensity, %) 332 (M^+, 10), 301 (15), 218 (44), 203 (19), 187 (92), 89 (25), 83 (base peak), and 73 (87). HRMS Found: m/z 332.1835. Calcd for $C_{15}H_{32}O_4Si_2$: M, 332.1837.

Dimethyl 2-Propyl-2,4-bis(trimethylsilyl)pentanedioate (8b): Colorless liquid; bp 230 °C/3332 Pa (bulb-to-bulb); IR (neat) 1715, 1250, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.06, 0.07 (each 9H, s, Me_3Si), 0.83 (3H, t, J=6.5 Hz, n-Pr), 1.1—2.1 (7H, m, 3-, 4-H, and n-Pr), and 3.58 (6H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−3.00, −2.29 (each q, Me_3Si), 15.11 (q, n-Pr), 19.65, 28.53, 33.65 (each t, n-Pr and 3-C), 35.00 (d, 4-C), 44.47 (s, 2-C), 51.06 (q, COOMe), and 176.88 (s, COOMe); MS m/z (rel intensity, %) 346 (M^+, 4), 201 (16), 97 (22), 89 (21), and 73 (base peak). HRMS Found: m/z 346.1992. Calcd for $C_{16}H_{34}O_4Si_2$: M, 346.1991.

Dimethyl 2-Butyl-2,4-bis(trimethylsilyl)pentanedioate (8c): Pale yellow liquid; bp 250 °C/4000 Pa (bulb-to-bulb); IR (neat) 1720, 1250, 1200, 1155, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00 (18H, s, Me_3Si), 0.6—2.1 (12H, m, n-Bu, 3-, and 4-H), 3.48, and 3.50 (each 3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−3.06, −2.35 (each q, Me_3Si), 13.82 (q, n-Bu), 23.83, 28.41, 28.65, 31.12 (each t, n-Bu and 3-C), 34.95 (d, 4-C), 44.30 (s, 2-C), 50.89 (q, COOMe), and 176.78 (s, COOMe); MS m/z (rel intensity, %) 360 (M^+, 8), 218 (22), 215 (37), 111 (47), 99 (10), 89 (28), and 73 (base peak). HRMS Found: m/z 360.2155. Calcd for $C_{17}H_{36}O_4Si_2$: M, 360.2150.

Dimethyl 2-Pentyl-2,4-bis(trimethylsilyl)pentanedioate (8d): Colorless liquid; bp 250 °C/3332 Pa (bulb-to-bulb); IR (neat) 1720, 1260, 1150, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.05, 0.06 (each 9H, s, Me_3Si), 0.7—2.1 (14H, m, n-C_5H_{11}, 3-, and 4-H), 3.57, and 3.59 (each 3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−3.10, −2.29 (each q, Me_3Si), 14.18 (q, n-C_5H_{11}), 22.53, 26..06, 28.71; 31.41, 33.12 (each t, n-C_5H_{11} and 3-C), 35.09 (d, 4-C), 44.36 (s, 2-C), 50.89 (q, COOMe), and 176.83 (s, COOMe); MS m/z (rel intensity, %) 374 (M^+, 13), 229 (34), 218 (19), 159 (16), 125 (26), 89 (27), and 73 (base peak). HRMS Found: m/z 374.2309. Calcd for $C_{18}H_{38}O_4Si_2$: M, 374.2306.

Dimethyl 2-(2-Methylpropyl)-2,4-bis(trimethylsilyl)pentanedioate (8e): Purified by silica-gel column chromatography with hexane–diethyl ether (10:1 v/v). Pale yellow liquid; bp 250 °C/4000 Pa (bulb-to-bulb); IR (neat) 1720, 1250, 1205, 1155, and 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.00, 0.05 (each 9H, s, Me_3Si), 0.72, 0.79 (each 3H, d, J=6.0 Hz, i-Bu), 1.4—2.3 (H, m, i-Bu, 3-, and 4-H), 3.46, and 3.52 (each 3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−2.82, −2.12 (each q, Me_3Si), 23.60, 24.35 (each q, i-Bu), 26.24, 30.71 (each t, i-Bu and 3-C), 34.41 (d, 4-C), 40.89 (s, 2-C), 42.12 (d, i-Bu), 50.77, 51.00 (each q, COOMe), 176.72, and 177.25 (each s, COOMe); MS m/z (rel intensity, %) 360 (M^+, 5), 317 (16), 213 (20), 111 (23), 109 (22), 89 (30), and 73 (base peak). HRMS Found: m/z 360.2165. Calcd for $C_{17}H_{36}O_4Si_2$: M, 360.2150.

Dimethyl 2-(3-Methylbutyl)-2,4-bis(trimethylsilyl)pentanedioate (8f): Pale yellow liquid; bp 240 °C/4000 Pa (bulb-to-bulb); IR (neat) 1720, 1255, 1200, 1160, and 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.08 (18H, s, Me_3Si), 0.7—1.8 (13H, m, i-C_5H_{11} and 3-H), 1.8—2.1 (1H, m, 4-H), 3.57, and 3.58 (each 3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−3.00, −2.24 (each q, Me_3Si), 22.36, 22.59 (each q, i-C_5H_{11}), 28.88, 29.36, 34.94 (each t, i-C_5H_{11} and 3-C), 35.12 (d, 4-C), 39.83 (d, i-C_5H_{11}), 44.24 (s, 2-C), 50.94 (q, COOMe), and 176.95 (s, COOMe); MS m/z (rel intensity, %) 374 (M^+, 7), 229 (30), 218 (16), 89 (28), and 73 (base peak). HRMS Found: m/z 374.2308. Calcd for $C_{18}H_{38}O_4Si_2$: M, 374.2306.

Methyl 4-Methyl-2-(trimethylsilyl)pentanoate (9): This compound **9** was purified through column chromatography on silica gel with hexane–diethyl ether (20:1 v/v). Obtained as a volatile compound contaminated by a trace of

8e, for which only IR ^{1}H, and ^{13}C NMR spectra were recorded. Colorless liquid; IR (neat) 1720, 1240, and 835 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.04 (9H, s, Me_3Si), 0.84, 0.86 (each 3H, d, J=7.0 Hz, *i*-Bu), 1.10 (1H, ddd, J_{gem}=12.5, J_{3-4}=8.7, and 2.0 Hz, one of 3-H), 1.2—1.6 (1H, m, *i*-Bu), 1.81 (1H, dt, J_{gem}=12.5, J_{3-4}=12.5, and 4.2 Hz, the other of 3-H), 2.06 (1H, dd, J_{4-3}=12.5 and 2.0 Hz, 4-H), and 3.60 (3H, s, COOMe); ^{13}C NMR ($CDCl_3$) δ=−2.82 (q, Me_3Si), 21.35, 23.12 (each q, *i*-Bu), 28.53 (t, 3-C), 35.60 (s, 2-C), 35.80 (d, 4-C), 50.94 (q, COOMe), and 176.36 (s, COOMe).

Dimethyl 2-Benzyl-2,4-bis(trimethylsilyl)pentanedioate (8g and 8g′) and Dimethyl 2-Benzyl-4-methoxycarbonyl-2,4,6-tris(trimethylsilyl)heptanedioate (10): The THF solution (5 ml) of phenyllithium (1M in benzene/diethyl ether, 1 ml, 1 mmol) was cooled down to −78 °C. To this solution was added under nitrogen **1** (0.474 g, 3 mmol) in THF. The mixture was stirred at −78 °C for 20 h, poured into saturated aqueous ammonium chloride, and extracted with diethyl ether (20 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed on silica gel with hexane–diethyl ether (5 : 1 v/v) to give an inseparable mixture of **8g** and **8g′** (0.144 g, 37%, 2 : 3 by ^{1}H NMR) and then **10** (0.257 g, 47%, isomer ratio: 7 : 1 by ^{1}H NMR). Pure **8g** can be obtained from the reaction of **1** with phenylmagnesium bromide: Phenylmagnesium bromide was prepared from Mg (0.024 g, 1 mmol) and phenyl bromide (0.157 g, 1 mmol) in dry diethyl ether (10 ml). To this solution was added at −15 °C under nitrogen **1** (0.316 g, 2 mmol) in diethyl ether (2 ml). After stirring was continued for 1 h at −15 °C, the mixture was poured into saturated aqueous ammonium chloride and extracted with diethyl ether (30 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed on silica gel with hexane–diethyl ether (5 : 1 v/v) to give **8g** (0.341 g, 87%).

Compounds **8g** and **10** are known.[3] Isomer **8g′** could not be separated from the mixture with **8g**. Partial spectral data of **8g′**: ^{1}H NMR ($CDCl_3$) δ=−0.02, 0.08 (each 9H, s, Me_3Si), 2.0—2.4 (3H, overlapping with signals of **8g**, 3- and 4-H), 2.93, 3.16 (each 1H, J_{gem}=13.5 Hz, $PhCH_2$), 3.62, and 3.70 (each 3H, s, COOMe). ^{13}C NMR ($CDCl_3$) δ=−2.76, −2.16 (each Me_3Si), 30.50 (3-C), 33.74 ($PhCH_2$), 39.60 (4-C), and 43.25 (2-C). Other signals are overapping with those of **8g**.

Methyl 5-Oxo-5-phenyl-2-(trimethylsilyl)pentanoate (11) and Dimethyl (2-Oxo-3-phenylpropyl)-2,4-bis(trimethylsilyl)pentanedioate (14): To the freshly prepared LDA (1.5 mmol) in dry THF (5 ml) was added at −78 °C under dry nitrogen acetophenone (0.18 g, 1.5 mmol) in THF (1 ml). After 20 min, **1** (0.158 g, 1 mmol) in THF (1 ml) was added. The mixture was stirred at −78 °C for 30 min, at room temperature for 1 h, poured into saturated aqueous ammonium chloride, and extracted with diethyl ether (15 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed on silica gel with hexane–diethyl ether (5 : 1 v/v) to give **11** (0.074 g, 27%) and then a mixture of two isomers of **14** (0.069 g, 30%, 8 : 1 by ^{1}H NMR).

11: Pale yellow liquid; IR (neat) 1700, 1680, 1245, 1200, and 840 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.11 (9H, s, Me_3Si), 1.9—2.2 (3H, m, 2- and 3-H), 2.88 (1H, ddd, J_{gem}=18.0, J_{4-3}=8.1, and 7.9 Hz, one of 4-H), 3.15 (1H, ddd, J_{gem}=18.0, J_{4-3}=8.5, and 5.1 Hz, the other of 4-H), 3.66 (3H, s, COOMe), 7.4—7.6 (3H, m, Ph), and 7.9—8.0 (2H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−2.68 (Me_3Si), 21.43 (3-C), 37.02 (2-C), 38.86 (4-C), 51.04 (COOMe), 128.07, 128.58, 133.01, 136.90 (each Ph), 175.59 (COOMe), and 199.85 (PhCO); MS *m/z* (rel intensity, %) 278 (M^+, 11), 246 (26), 218 (26), 159 (40), 146 (20), 105 (base peak), 89 (21), 77 (51), and 73 (65). HRMS Found: *m/z* 278.1349. Calcd for $C_{15}H_{22}O_3Si$: M, 278.1360.

14: Pale yellow liquid; IR (neat) 1700, 1450, 1250, 1200, 1150, and 840 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.09, 0.14 (each 9H, s, Me_3Si), 1.9—2.3 (5H, m, CH_2 and CH), 3.11 (2H, dd, J=9.5 and 8.0 Hz, $COCH_2$), 3.47, 3.65 (each 3H, s, COOMe), 7.4—7.6 (3H, m, Ph), and 7.9—8.0 (2H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−2.98, −2.40 (each Me_3Si), 25.30, 28.98, 35.00, 35.75 (each CH_2 and CH), 43.34 (2-C), 51.11, 51.17 (each COOMe), 128.02, 128.55, 132.81, 137.12 (each Ph), 176.24, 176.57 (each COOMe), and 199.88 (PhCO); MS *m/z* (rel intensity, %) 436 (M^+, 6), 218 (11), 192 (13), 159 (14), 105 (68), 89 (21), 77 (46), 75 (13), and 73 (base peak). HRMS Found: *m/z* 436.2104. Calcd for $C_{22}H_{36}O_5Si_2$: M, 436.2099.

2-Benzyl-2,4-bis(trimethylsilyl)-1,5-pentanediol (16): To a solution of lithium aluminum hydride (LAH, 0.16 g, 4 mmol) in dry diethyl ether (2 ml) was added dropwise **7c** (0.198 g, 0.5 mmol) in diethyl ether (2 ml). After stirred at room temperature for 3 h, the mixture was poured into ice-cold aqueous potassium sodium tartrate and extracted with diethyl ether (15 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo to give **16** (0.169 g, 100%). A similar treatment of **8g** with LAH gave **16** in a quantitative yield. This compound **16** was submitted to the subsequent cyclization into **17** without further purification. **16**: Colorless liquid; IR (neat) 3300, 1245, 1030, and 825 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.04, 0.06 (each 9H, s, Me_3Si), 1.05 (1H, ddt, J_{4-3}=11.7, 3.2, and J_{4-5}=3.7 Hz, 4-H), 1.59 (1H, dd, J_{gem}=15.1 and J_{3-4}=3.2 Hz, one of 3-H), 1.84 (1H, dd, J_{gem}=15.1 and J_{3-4}=11.7 Hz, the other of 3-H), 2.58 (2H, br s, OH), 2.70, 2.83 (each 1H, d, J_{gem}=13.1 Hz, $PhCH_2$), 3.66 (1H, dd, J_{gem}=11.7 and J_{5-4}=3.7 Hz, one of 5-H), 3.90 (1H, dd, J_{gem}=11.7 and J_{5-4}=3.7 Hz, the other of 5-H), 3.96 (2H, s, 1-H), and 7.2—7.3 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−2.12, −1.63 (each Me_3Si), 27.10 (3-C), 29.50 (4-C), 34.80 (2-C), 42.78 ($PhCH_2$), 63.94, 66.38 (1- and 5-C), 126.29, 128.17, 130.23, and 139.84 (each Ph).

3-Benzyl-*r*-3,*t*-5-bis(trimethylsilyl)perhydropyran (17): To a solution of **16** (0.052 g, 0.15 mmol) in THF (1.5 ml) was added at −78 °C butyllithium (1.6 M in hexane, 0.09 ml, 0.15 mmol). After 30 min, *p*-toluenesulfonyl chloride (0.028 g, 0.15 mmol) was added and the stirring was continued at the same temperature for 2 h. Another portion of butyllithium (0.09 ml, 0.15 mmol) was added. The mixture was stirred at −78 °C for 3 h, at room temperature for 12 h, poured into ice-cold saturated aqueous ammonium chloride, and extracted with diethyl ether (10 ml×2). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed on silica gel by using hexane–diethyl ether (20 : 1 v/v) to give **17** (0.027 g, 55%): Colorless liquid; IR (neat) 1245, 1090, 1070, and 830 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=−0.09, 0.11 (each 9H, s, Me_3Si), 1.2—1.3 (2H, 4-H_{ax} and 5-H), 1.78 (1H, m, 4-H_{eq}), 2.48 (2H, s, $PhCH_2$), 2.95 (1H, m, 6-H_{ax}), 3.12 (1H, d, J_{gem}=11.4 Hz, 2-H_{ax}), 3.8—3.9 (1H, m, 6-H_{eq}), 3.99 (1H, dd, J_{gem}=11.4 and J_{2-6}=2.2 Hz, 2-H_{eq}), 7.0—7.1 (3H, m, Ph), and 7.2—7.3 (2H, m, Ph); MS *m/z* (rel intensity, %) 320 (M^+, 8), 231 (24), 230

(base peak), 190 (12), 189 (35), 188 (52), 158 (19), 143 (27), and 73 (12). HRMS Found: m/z 320.1991. Calcd for $C_{18}H_{32}OSi_2$: M, 320.1991.

References

1) O. Tsuge, S. Kanemasa, and Y. Ninomiya, *Chem. Lett.*, **1984**, 1993.

2) S. Kanemasa, H. Kobayashi, J. Tanaka, and O. Tsuge, *Bull. Chem. Soc. Jpn.*, **61**, 3957 (1988); J. Tanaka, H. Kobayashi, S. Kanemasa, and O. Tsuge, *ibid.*, **62**, 1193 (1989).

3) J. Tanaka, S. Kanemasa, Y. Ninomiya, and O. Tsuge, *Bull. Chem. Soc. Jpn.*, **63**, 446 (1990).

4) P. F. Hudrlik, D. Peterson, and D. Chou, *Synth. Commun.*, **5**, 359 (1975); P. A. Grieco, C. -L. J. Wang, and S. D. Burke, *J. Chem. Soc., Chem. Commun.*, **1975**, 537; L. A. Paquette, G. D. Maynard, C. S. Ra, and M. Hoppe, *J. Org. Chem.*, **54**, 1408 (1989).

5) Part of the stereoselective protonation has been reported as a preliminary communication (J. Tanaka, S. Kanemasa, H. Kobayashi, and O. Tsuge, *Chem. Lett.*, **1989**, 1453).

6) Transmetallation of this lithium enolate was attempted by use of magnesium bromide etherate, but a mixture of complex products resulted after the reaction with **1**.

7) M. Yamaguchi, M. Tsukamoto, S. Tanaka, and I. Hirao, *Tetrahedron Lett.*, **25**, 5661 (1984).

8) Trapping the adduct anion **E** by *O*-silylation failed, where both trimethylsilyl and *t*-butyldimethylsilyl chlorides were employed as trapping agents (R. E. Ireland, R. H. Mueller, and A. K. Willard, *J. Am. Chem. Soc.*, **98**, 2868 (1976); C. H. Heathcock, C. T. Buses, W. A. Kleschick, M. C. Pirrung, J. E. Sohn, and J. Lampe, *J. Org. Chem.*, **45**, 1066 (1980).

9) For a review, see: L. Duhamel, P. Duhamel, J. C. Launay, and J. C. Plaquevent, *Bull. Soc. Chim. Fr.*, **1984**, 412.

10) I. Fleming, R. Henning, and H. Plaut, *J. Chem. Soc., Chem. Commun.*, **1984**, 28.

11) S. Takano, J. Kudo, M. Takahashi, and K. Ogasawara, *Tetrahedron Lett.*, **27**, 2405 (1986) and the references cited therein.