Radical Cyclization in Heterocycle Synthesis. 12.[1] Sulfanyl Radical Addition–Addition–Cyclization (SRAAC) of Unbranched Diynes and Its Application to the Synthesis of A-Ring Fragment of 1α,25-Dihydroxyvitamin D_3

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Sulfanyl radical addition–addition–cyclization (SRAAC) of unbranched diynes proceeded smoothly to give cyclized *exo*-olefins, while the sulfanyl radical addition–cyclization–addition (SRACA) of diynes having a quaternary carbon gave cyclized *endo*-olefins. This method was successfully applied to the synthesis of A-ring fragment of 1α,25-dihydroxyvitamin D_3.

Key words sulfanyl radical; addition–addition–cyclization; diyne; alkylidenecyclopentane; alkylidenecyclohexane; vitamin D

Radical cyclization is a useful method for the preparation of various cyclic compounds.[1] Recently, this method in which carbon centered radical species are generated by the addition reaction of a radical to a multiple bond has drawn the attention of synthetic chemists because of its several advantages, such as readily available starting substrate and formation of functionalized products. The synthetic utility of this type of approach using diene and enyne systems has been partially shown.[2,3] To our knowledge, there have been only a few papers published on the radical cyclization of diynes,[4] which requires drastic conditions for successful radical cyclization. Furthermore, diynes **1** (X=C(COOMe)$_2$) having a quaternary carbon have been employed as substrates, because the cyclization reaction is facilitated by the Thorpe–Ingold effect and reactive rotamer effect.[5] Unbranched diyne **1** (X=CH$_2$) has been reported to yield no cyclized product but only an acyclic adduct.[4a,6] We found that the sulfanyl radical-induced cyclization of unbranched diyne **1** (X=CH$_2$) proceeded smoothly by employing 2 eq of thiophenol under mild conditions to give cyclized product **2** as the major product in moderate yield (Chart 1). Additionally, we disclosed that the feasibility of the sulfanyl radical addition and/or cyclization is dependent upon the structure of the substrates. In the case of unbranched 1,6-heptadiyne **1** (n=1, X=CH$_2$), sulfanyl radical addition–addition–cyclization (SRAAC) proceeded smoothly to give cyclized product **2** having an *exo*-olefin as the major product, while in the case of 1,6-heptadiyne **1** (n=1, X=C(COOMe)$_2$, NTs) having either a quaternary carbon or a heteroatom, sulfanyl radical addition–cyclization–addition (SRACA) occurred to give *endo*-olefin **3**. In the case of longer carbon chain, **1** (n=2, X=CH$_2$, C(COOMe)$_2$) gave *exo*-olefin **2** as the major product, while **1** (n=2, X=NSO$_2$Ar) gave a complex mixture. Synthetic utility of newly found SRAAC has been proved by a novel synthesis of A-ring fragment **5** of 1α,25-dihydroxyvitamin D_3 (1α,25-(OH)$_2$D$_3$).

Results and Discussion

SRAAC and SRACA to Diynes We first investigated the radical cyclization of the readily available diynes **6a**—**d**[7,8] (Chart 2, Table 1). A solution containing thiophenol (1 eq) and 2,2′-azobisisobutyronitrile (AIBN) (0.5 eq) in benzene was added dropwise to a solution of an unbranched diyne, 1,6-heptadiyne (**6a**) in boiling benzene while stirring under nitrogen. The solution was then refluxed for a further 2 h and separation of the crude product gave the cyclic products **7a** (E:Z= 10 : 1) and **8a** in 21 and 19% yields, respectively, along with the recovered volatile starting material **6a** and acyclic adduct **10a** as a mixture of (E)- and (Z)-isomers (entry 1). **10a** was also obtained but in 17% yield by radical reaction of **6a** using 2,2′-azobis(2,4-dimethyl-4-methoxyvaleronitrile) (V-70)[9] as radical initiator at room temperature. When 2 eq of thiophenol was used in the presence of AIBN, the reaction proceeded smoothly to give the *exo*-olefin **7a** (E:Z=8 : 1) having two sulfanyl groups in 70% yield as the major product (entry 2). On the other hand, the branched

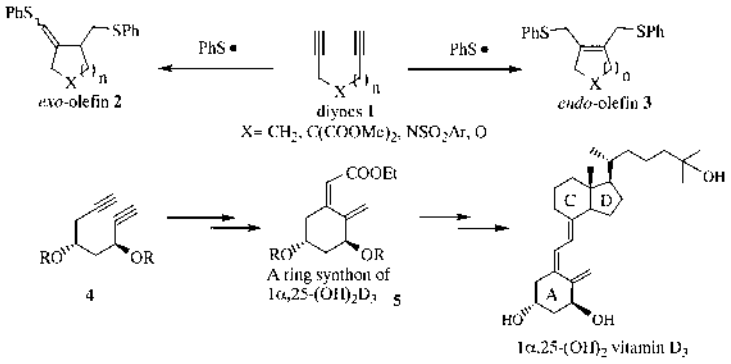

Chart 1

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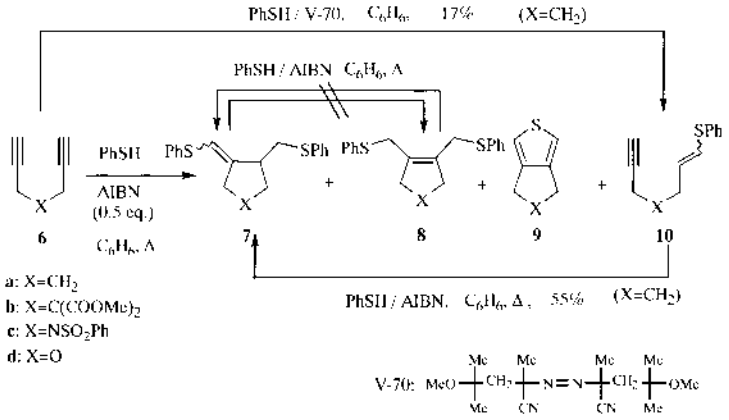

Chart 2

Table 1. Sulfanyl Radical Addition–Cyclization Reaction of 1,6-Diynes

Entry	Substrate	PhSH (eq)	Yield (%)				
			Total	**7**	**8**	**9**	**10**
1	**6a**	1	53	21 ($E:Z$=10 : 1)	19	—	13
2	**6a**	2	96	70 ($E:Z$= 8 : 1)	26	—	—
3	**6b**	2	96	—	86	10	—
4	**6c**	2	92	20 (only Z)	55	17	—
5	**6d**	2	57	10 (only Z)	28	19	—

diyne **6b** having a quaternary carbon afforded the *endo*-olefin **8b**[10] in 86% yield along with a small amount of thiophene **9b**[11a] and with no detection of *exo*-olefin **7b** (entry 3). Thus, it is interesting to note that radical cyclization of unbranched diyne **6a** gave the *exo*-olefin **7a** as the major product, while branched diyne **6b** provided the *endo*-olefin **8b**. Radical addition–cyclization of diynes **6c** and **6d** having a heteroatom (X=NSO_2Ar or O) as the X group, gave the *endo*-olefins **8c** and **8d** as the major product in 55 and 28% yields, respectively. In both cases, *exo*-olefins **7c**, **d** (*Z*-isomer) and thiophenes **9c**, **d**[4b,11b] were obtained as shown in Table 1.

In order to explain the reaction pathway to these products, we examined the equilibration between the *exo*- and *endo*-products as well as a radical reaction of acyclic adduct **10a**. Under the radical reaction conditions, no equilibration between **7a** and **8a** was observed and acyclic adduct **10a** gave exclusively **7a** with no detection of two compounds, **8a** and **9a**. Therefore, we propose a plausible reaction pathway as shown in Chart 3. Since unbranched diyne **6a** would exist normally in a stable zig-zag conformer **6A**, the hydrogen transfer from thiophenol to the resulting vinyl radical **C**, formed from diyne **6a** (X=CH_2) by the addition of a sulfanyl radical, occurs to give the adduct **10** in preference to intramolecular cyclization of **C**. As a next step, a sulfanyl radical attacks another terminal alkyne in **10** to give vinyl radical **D**. The vinyl radical **D** is less stable than cyclized radical **E**, which is stabilized by an adjacent sulfanyl group. Therefore, since the equilibrium between **D** and **E** favors radical **E**, the formation of cyclized *exo*-olefin **7** is preferable to that of the adduct **11**. On the other hand, diynes **6b**, **c** having either a quaternary carbon or a heteroatom (X=$C(COOMe)_2$ or NSO_2Ar) would exist preferentially in a conformer **6B** which is suitable for intramolecular cyclization compared to the less favored conformer **6A**, due to the steric repulsion between the substituents on the X group and the alkyne part. Therefore, addition of a sulfanyl radical to alkynes **6b**, **c** followed by cyclization of the resulting vinyl radical **F** gave the diene **H**, which underwent 1,4-radical addition of thiophenol to give **8**. Doubly cyclized thiophene **9** would be obtained *via* intramolecular S_Hi reaction[4b] of vinyl radical **G** on the phenylsulfanyl group.

After successful cyclization of 1,6-heptadiynes **6a**—**d**, we then extended the sulfanyl radical addition–cyclization to 1,7-octadiynes **12a**—**c**[7,12] (Chart 4, Table 2) and 1,8-nonadiyne (**17**)[7] (Chart 5). It is known[2f] that cyclization of 6-heptenyl radical proceeds about 40 times slower than that of the corresponding hexenyl radical. Cyclization of **12a** proceeded smoothly to give the desired *exo*-product **13a** ($E:Z$=5 : 2) in 69% yield. Radical reaction of **12b** having a quarternary carbon gave the *exo*-olefin **14b** as the major product (entry 1). However, **12c** having heteroatom gave a complex mixture of products from which (*E*)-*exo*-olefins **13c** and (*Z*)-*exo*-**14c**, and *endo*-olefin **15c** were isolated in 3, 9, and 25% yields, respectively (entry 2). To improve the yields of **13c** and **14c**, we examined the reaction procedure shown in entry 3. According to the reaction pathway for **7** shown in Chart 3, when excess thiophenol (hydrogen donor) is present in a reaction mixture, the hydrogen transfer from thiophenol to the corresponding vinyl radical (**C** type in Chart 3), formed from **12c** would proceed smoothly to give the adduct (**10** type in Chart 3) in preference to intramolecular cyclization of the vinyl radical (**C** type in Chart 3). Finally, the adduct would be converted into the desired products **13c** and **14c** *via* the sulfanyl radical addition to terminal alkyne followed by vinyl radical cyclization. Thus, it is expected that SRAAC reaction would be preferable to SRACA reaction under the reaction condi-

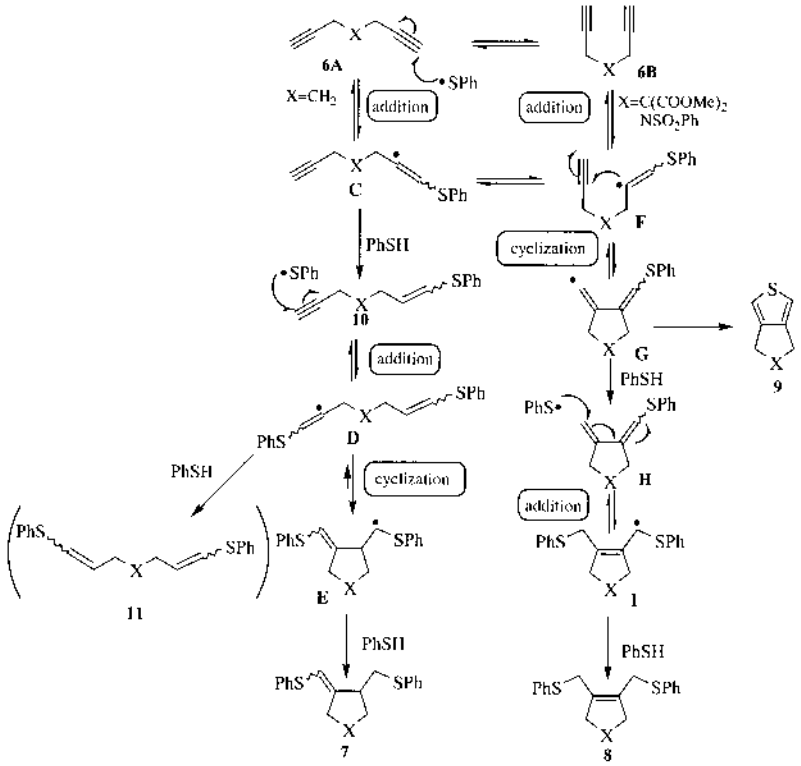

Chart 3

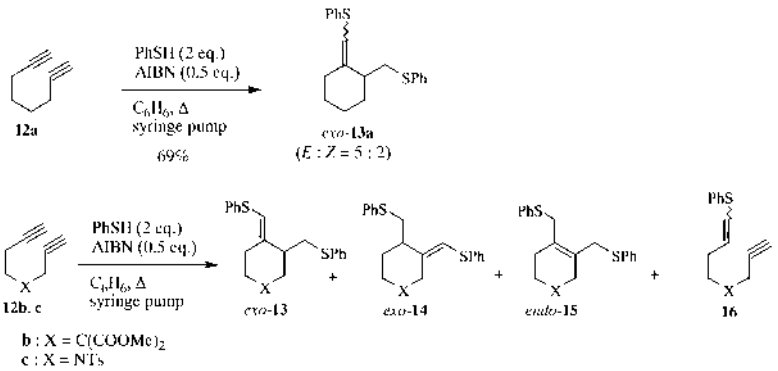

Chart 4

Table 2. Sulfanyl Radical Addition–Cyclization Reaction of 1,7-Diynes

Entry	Substrate	Yield (%)				
		Total	**13**	**14**	**15**	**16**
1	**12b**	87	6 (only *E*)	32 (only *E*)	14	20
2	**12c**	72	3 (only *E*)	9 (only *Z*)	25	33
3[a)]	**12c**	56	14 (only *E*)	25 (only *Z*)	17	0

a) Addition of PhSH (1 eq) and AIBN (0.5 eq) to a mixture of PhSH (1 eq) and **12c**.

tions. A mixture of thiophenol (1 eq) and AIBN was added to a refluxing solution of **12c** and thiophenol (1 eq) in benzene to give *exo*-olefins **13c** and **14c** as the major product monitoring no formation of acyclic adduct **16** (entry 3). Under the reaction conditions, no equilibration between **14c** and **15c** was observed.

1,8-Nonadiyne (**17**) did not undergo cyclization, but the adduct **18** was obtained quantitatively as a mixture of geometrical isomers as a result of addition of thiophenol to the alkynyl group (Chart 5).

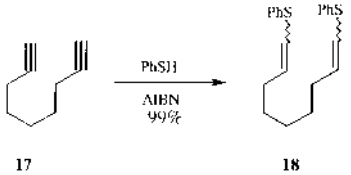

Chart 5

We speculated that the radical reaction of 1,7-octadiynes **12a**—**c** would take place by a similar reaction pathway to the case of formation of the 5-membered ring described in Chart 3 (Chart 6). The *exo*-products **13a**—**c** and **14b**, **c** were obtained *via* either route I or I′ by SRAAC reaction. The major reaction pathway would be route I that involves addition of sulfanyl radical to one of two alkynes which is less close to

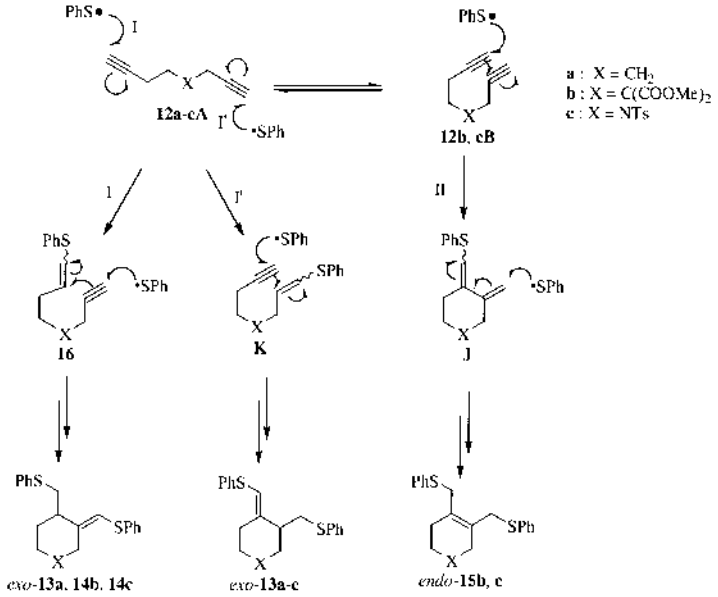

Chart 6

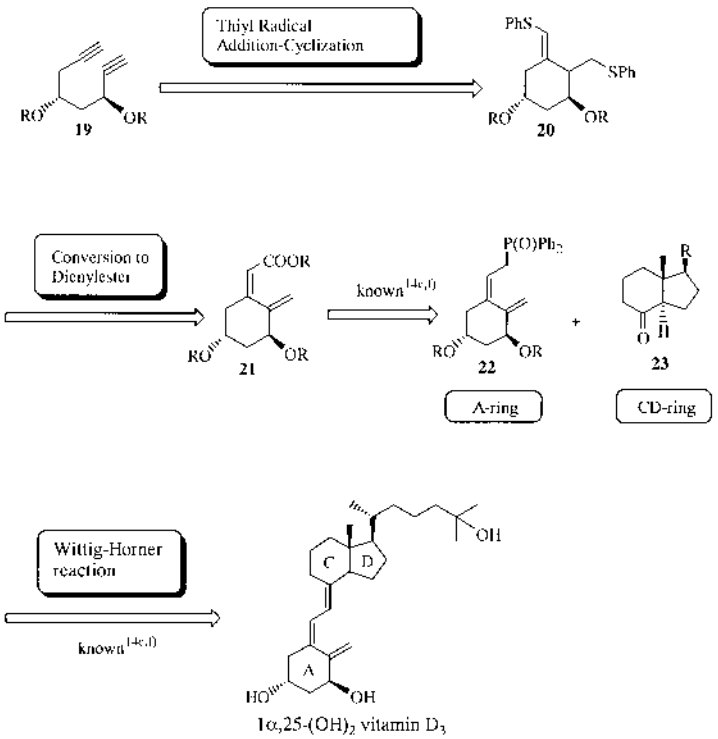

Chart 7

the X-group and therefore sterically less hindered. On the other hand, SRACA reaction of **12b**, **c** gave the *endo*-products **15b**, **c** *via* route II. In the case of diester, the 1,7-octadiyne **12b** gave a mixture of **13b**, **14b** and **15b** with predominant formation of *exo*-products **13b** and **14b** compared to *endo*-product **15b**.

The result is quite contrary to the radical reaction of 1,6-heptadiyne **6b** which afforded the *endo*-product **8b** as the major product as shown in Table 1. It is suggested that the radical cyclization of 1,7-octadiynes proceeds more slowly than that of 1,6-heptadiynes.

Synthesis of A-Ring Fragment of 1α,25-Dihydroxyvitamin D_3 Based on the results shown in the previous chapter, we undertook the synthesis of A-ring fragment of 1α,25-dihydroxyvitamin D_3. Since the discovery of 1α,25-dihydroxyvitamin D_3 as the active metabolite of vitamin D, many synthetic efforts have been made in this area.[13] Basic strategies[14] for the construction of 1α,25-dihydroxyvitamin D_3 mostly involve the coupling reaction of an A-ring precursor **22** with the CD-ring part **23** of the vitamin D skeleton (Chart 7). On the basis of Lythgoe's synthesis[14c,d] of vitamin D_3, a Hoffman-La Roche group[14e,f] achieved the synthesis of 1α,25-dihydroxyvitamin D_3 using **22** as a useful precursor of A-ring synthon. We investigated the synthesis of **21**, a known

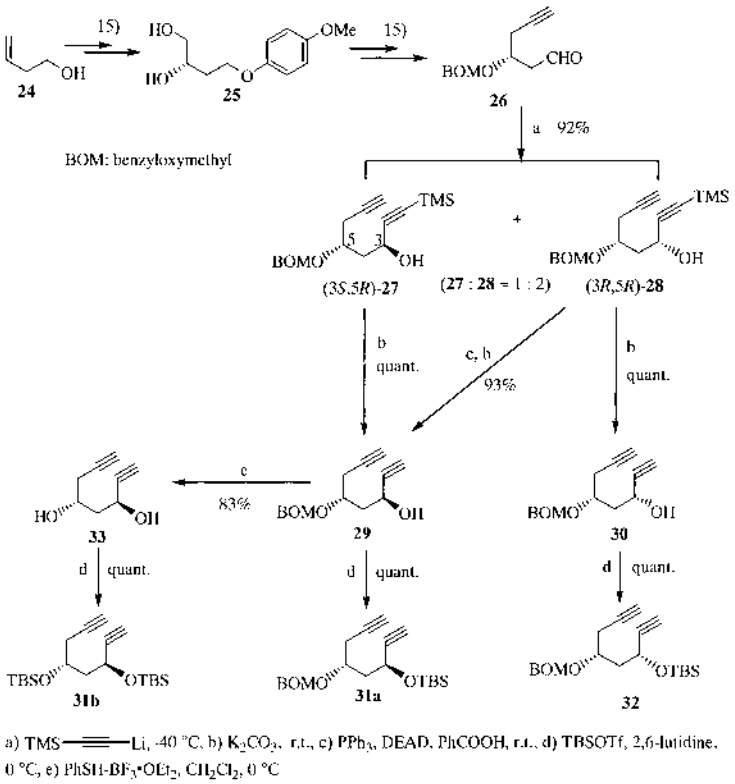

Chart 8

precursor[14e,f] of **22** using sulfanyl radical addition–cyclization of the diyne **19** as the key reaction.

We employed the diynes **31a**, **b** as the chiral substrate for radical addition–cyclization (Chart 8). **31a**, **b** were prepared from 3-buten-1-ol (**24**) as follows. According to the reported procedure,[15] the alcohol **24** was converted into the aldehyde **26** *via* protection of the hydroxy group in **24**, asymmetric dihydroxylation of the resulting olefin with AD-mix-α, monotosylation of the diol, transformation of the tosylate into the epoxide, introduction of acetylene unit, benzyloxymethylation, deprotection of the hydroxy group, and oxidation of the alcohol. Addition of lithium acetylide to the aldehyde **26** gave a 1 : 2 mixture of the diynes **27** and **28** in 92% combined yield. Desilylation of **27** and **28** with potassium carbonate afforded **29** and **30**, respectively. The diyne **29** also was prepared from **28** in 93% yield by epimerization of the hydroxyl group under Mitsunobu conditions. Furthermore, silylation of **29** and **30** with *tert*-butyldimethylsilyl trifluoromethanesulfonate (TBSOTf) gave **31a** and **32**, respectively. Disilyl ether **31b** was prepared from **29** *via* removal of the benzyloxymethyl (BOM) group followed by silylation of the resulting diol **33**. The configurations of **31a**, **b** were eventually deduced from analysis including nuclear Overhauser enhancement and exchange spectroscopy (NOESY) of the ^{1}H-NMR spectra of the cyclized products **34a**, **b** (Fig. 1).

We next investigated the sulfanyl radical addition–cyclization of substrates **31a**, **b** and **32** (Chart 9, Table 3). Sulfanyl radical addition–cyclization of **31a** in the presence of thiophenol and AIBN gave a separable mixture of **34a**, **35a**, and **36a** in combined 37% yield (entry 1). Similarly, **31b** underwent the radical cyclization to give **34b** and an inseparable mixture of **35b** and **36b** in combined 66% yield (entry 2).

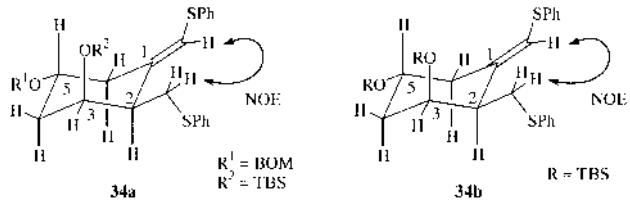

Fig. 1. NOE Correlations of Compounds **34a**, **b**

These stereostructures were deduced from comparison of the ^{1}H-NMR spectra with those of **35a** and **36a**, respectively. On the other hand, the attempted radical cyclization of **32** was unsuccessful and many uncharacterized products were formed. We are unable at this time to offer an explanation of the influence of stereochemistry at 3-position on the radical cyclization.

The stereostructures of **34a**, **b** were deduced from comparison of the ^{1}H-NMR spectra with those of the related compounds[16] and nuclear Overhanser effect (NOE) correlations as shown in Fig. 1. Both the stereostructures at 1-position and geometry of olefin **35a** were hardly discernible from the spectral analysis.

We next examined conversion of the main product **34b** into the A-ring synthon **40** (Chart 10). Oxidation of **34b** at 0 °C with *m*-chloroperbenzoic acid (mCPBA) gave the sulfoxide **37**, which was then subjected to pyrolysis to give the dienylsulfoxide **38**.

In order to introduce an alkoxycarbonyl group[17] at α-position, we started to investigate the model study using **42** as substrate, prepared from **13a** *via* pyrolytic elimination of the corresponding sulfoxide (Chart 11, Table 4). Treatment of **42** with methyllithium at −78 °C followed by acylation with

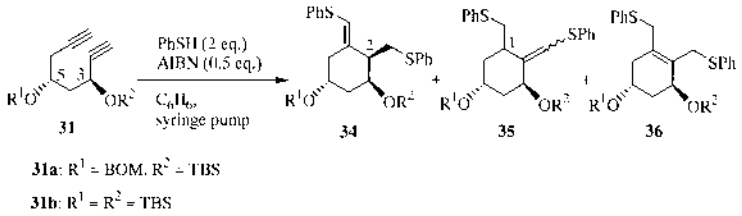

Chart 9

Table 3. Sulfanyl Radical Addition–Cyclization Reaction of **31a**, **b**

Entry	Substrate	Yield (%)			
		Total	**34**	**35**	**36**
1	**31a**	37	19	15	3
2	**31b**	66	38	28	

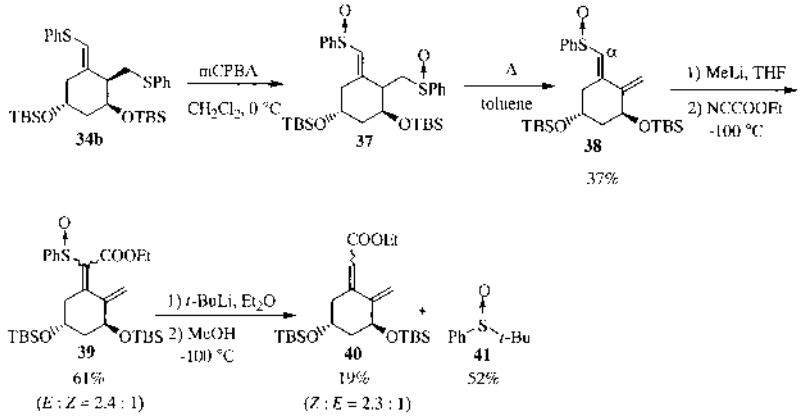

Chart 10

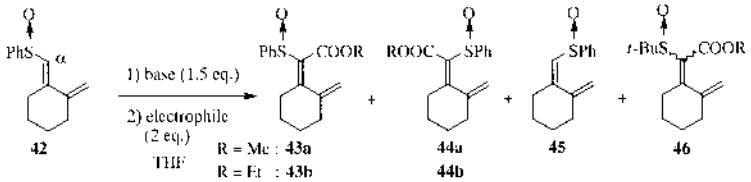

Chart 11

Table 4. Introduction of Alkoxycarbonyl Group

Entry	Base (1.5 eq)	Electrophile	R	Temp. (°C)	Time[a] (min)	Yield (%)			
						43	**44**	**45**	**46**
1	MeLi	ClCOOMe	Me	−78	30	6	9	—	—
2	MeLi	ClCOOMe	Me	−100	30	29	7	—	—
3	LDA	ClCOOMe	Me	−100	30	—	—	—	—[b]
4	*tert*-BiLi	ClCOOMe	Me	−100	30	—	—	—	16
5	MeLi	ClCOOMe	Me	−100	15	36	18	3	—
6	MeLi	ClCOOEt	Et	−100	15	49	13	—	—

a) Reaction time on lithiation of **42** with base before addition of electrophile. *b*) Recovery of **42**.

methyl chloroformate gave the desired products **43a** and **44a** in low yields (entry 1). Lowering the temperature from −78 to −100 °C improved the yield (36%) (entry 2). The attempted acylation using lithium diisopropylamide (LDA) as base was unsuccessful and the substrate **42** was mostly recovered (entry 3). Lithiation of **42** with *tert*-butyllithium fol-

lowed by acylation gave *tert*-butyl sulfoxide **46** in low yield, which would be formed as the result of attack of *tert*-butyllithium on both sulfur atom and vinyl proton. Unfortunately, **43a** and **44a** could not be detected in the reaction mixture (entry 4). When the reaction time for lithiation of **42** with methyl lithium was shortened from 30 min to 15 min, the desired products **43a** and **44a** were obtained in 54% combined yield (entry 5). When ethyl cyanoformate was used as acylating reagent, the yield of these two products was improved (62%) (entry 6).

Based on the preliminary experimental results, we next examined the acylation of vinyl sulfoxide **38** under the best conditions shown in entry 6 of Table 4 (Chart 10). The desired product **39** was obtained in 61% yield and in 2.4 : 1 ratio of (*E*)- and (*Z*)-isomers. Desulfurization of (*E*)-isomer **39** was achieved by Theobald's method.[18] (*E*)-**39** was treated with *tert*-butyllithium at −100 °C to give a 2.3 : 1 mixture of the (*Z*)- and (*E*)-α,β-unsaturated esters **40** along with *tert*-butyl phenylsulfoxide **41**. To improve the yield of the desired product **40**, we examined desulfurization under different conditions; however, no other reactions than Theobald's method gave this product.[19] It is known[14f] that (*E*)-isomer **40** is photochemically convertible to (*Z*)-**40** in good yield, which is the key intermediate for the synthesis of 1α,25-dihydroxyvitamin D_3. The physical and spectral data of the (*Z*)-ester **40** ($[\alpha]_D^{22}$ −38.1° (*c*=0.11, Et_2O)) were identical with those ($[\alpha]_D^{25}$ −36.9° (*c*=0.3, Et_2O)) of the authentic sample reported in the literature.[14f] Since (*Z*)-**40** had previously been converted into 1α,25-dihydroxyvitamin D_3 *via* reduction of the ester, transformation into phosphine oxide, Wittig reaction, and finally deprotection, the present method provides a new synthesis of 1α,25-dihydroxyvitamin D_3.

In conclusion, we have developed for the first time SRAAC of unbranched diynes. In the case of unbranched 1,6-heptadiyne, SRAAC proceeded smoothly to give the cyclized product having an *exo*-olefin as the major product. Similarly, in the case of 6-membered ring formation, the *exo*-olefin was obtained as a major product. Furthermore, we achieved the synthesis of A-ring fragment of 1α,25-dihydroxyvitamin D_3 (1α,25-$(OH)_2D_3$) *via* the route involving SRAAC of diyne **31b**.

Experimental

General Melting points are uncorrected. ^{1}H- and ^{13}C-NMR spectra were recorded at 200, 300, or 500 MHz and at 50 or 125 MHz, respectively. IR spectra were recorded using FTIR apparatus. The data without special peaks in IR spectra are not shown here. Mass spectra were obtained by electron-impact ionization (EI) method. Flash column chromatography was preformed using E. Merck Kieselgel 60 (230—400 mesh). Medium-pressure column chromatography was performed using Lober größe B (E. Merck 310-25, Lichroprep Si60). Short column chromatography was undertaken on a short glass filter using E. Merck Kieselgel 60 (230—400) under reduced pressure.

Sulfanyl Radical Reaction of Diynes 6a—d (Table 1) To a boiling solution of the diynes **6a**—**d**[7] (1 mmol) in benzene (10 ml) was added a solution of thiophenol (1—2 mmol) and AIBN (0.5 mmol) in benzene (10—20 ml) under nitrogen atmosphere by a syringe pump (3—5 ml/h) over 2 h. After being heated at reflux for a further 4 h, the reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane/AcOEt) afforded the cyclized compounds **7**, **8**, **9**, and the adduct **10** as shown in Table 1.

(*E*)-[[[2-[(Phenylthio)methyl]cyclopentylidene]methyl]thio]benzene [(*E*)-**7a**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.57—1.71 (2H, m), 1.78—1.86 (1H, m), 2.00—2.07 (1H, m), 2.36—2.50 (2H, m), 2.75—2.82 (1H, m), 2.91 (1H, dd, *J*=12.5, 9 Hz), 3.21 (1H, dd, *J*=12.5, 5 Hz), 6.13 (1H, br q, *J*=2 Hz), 7.15—7.20 (2H), 7.25—7.36 (8H) (each m). NOE was observed between methylene-H (δ 2.91, 3.21) and olefinic-H (δ 6.13) in NOESY spectroscopy. HRMS *m/z*: 312.1020 (Calcd for $C_{19}H_{20}S_2$: 312.1006).

(*Z*)-[[[2-[(Phenylthio)methyl]cyclopentylidene]methyl]thio]benzene [(*Z*)-**7a**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.60—1.69 (1H, m), 1.74—1.83 (1H, m), 1.88—1.94 (2H, m), 2.39—2.53 (2H, m), 2.71 (1H, dd, *J*=13, 6 Hz), 3.00—3.07 (1H, m), 3.48 (1H, dd, *J*=13, 3.5 Hz), 6.09 (1H, br q, *J*=2 Hz), 7.13—7.20 (2H), 7.24—7.31 (6H), 7.40—7.43 (2H) (each m). NOE was observed between methylene-H (δ 2.71, 3.48) and ArH (δ 7.40—7.43) in NOESY spectroscopy. HRMS *m/z*: 312.1020 (Calcd for $C_{19}H_{20}S_2$: 312.1006).

1,2-Bis[(phenylthio)methyl]cyclopentene (**8a**): A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.79 (2H, quint., *J*=7.5 Hz), 2.44 (4H, t, *J*=7.5 Hz), 3.34 (4H, br s), 7.16—7.33 (10H, m). HRMS *m/z*: 312.0999 (Calcd for $C_{19}H_{20}S_2$: 312.1006).

(*E*/*Z*)-1-Phenylthio-1-hepten-6-yne (**10a**): A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.67 (2H, quint., *J*=7.5 Hz), 1.96—2.00 (1H, m), 2.21—2.42 (4H, m), 5.80 (1/2H, dt, *J*=9, 7 Hz), 5.94 (1/2H, dt, *J*=14.5, 7 Hz), 6.17—6.28 (1H, m), 7.16—7.53 (5H, m). HRMS *m/z*: 202.0821 (Calcd for $C_{13}H_{14}S$: 202.0816).

Dimethyl 3,4-Bis[(phenylthio)methyl]-3-cyclopentene-1,1-dicarboxylate (**8b**): A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 3.12 (4H, br s), 3.18 (4H, br s), 3.72 (6H, s), 7.18—7.38 (10H, m). IR ($CHCl_3$) cm^{-1}: 1740 (COO). HRMS *m/z*: 428.1129 (Calcd for $C_{23}H_{24}O_4S_2$: 428.1116).

Dimethyl 4*H*-Cyclopenta[*c*]thiophene-5,5(6*H*)-dicarboxylate (**9b**)[11a]: Pale yellow crystals. mp 79—81 °C (Et_2O). ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 3.35 (4H, br s), 3.71 (6H, s), 6.81 (2H, s). IR ($CHCl_3$) cm^{-1}: 1734 (COO). HRMS *m/z*: 240.0479 (Calcd for $C_{11}H_{12}O_4S$: 240.0456). *Anal*. Calcd for $C_{11}H_{12}O_4S$: C, 54.99; H, 5.03. Found: C, 54.87; H, 4.96.

(*Z*)-1-(Phenylsulfonyl)-4-[(phenylthio)methyl]-3-[(phenylthio)methylidene]-pyrrolidine [(*Z*)-**7c**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 2.79 (1H, dd, *J*=13, 9 Hz), 2.87—2.94 (1H, m), 3.08 (1H, dd, *J*=13, 5.5 Hz), 3.32 (1H, dd, *J*=10, 5 Hz), 3.47 (1H, dd, *J*=10, 7 Hz), 3.90 (1H, ddd, *J*=15, 2.5, 1.5 Hz), 3.93 (1H, ddd, *J*=15, 2.5, 2 Hz), 6.13 (1H, td, *J*=2, 1.5 Hz), 7.19—7.31 (10H), 7.52—7.56 (2H), 7.59—7.64 (1H), 7.82—7.85 (2H) (each m). NOE was observed between methylene-H (δ 3.08) and olefinic-H (δ 6.13) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 37.29, 43.29, 50.92, 52.81, 117.57, 126.74, 126.94, 127.81, 129.16, 129.19, 129.20, 130.02, 132.99, 134.97, 135.09, 139.90. HRMS *m/z*: 453.0884 (Calcd for $C_{24}H_{23}NO_2S_3$: 453.0891).

1-(Phenylsulfonyl)-3,4-bis[(phenylthio)methyl]-2,5-dihydro-1*H*-pyrrole (**8c**): Pale yellow crystals. mp 94—95°C (Et_2O). ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.97 (4H, br s), 4.15 (4H, br s), 7.06—7.27 (10H), 7.54—7.68 (3H), 7.81—7.87 (2H) (each m). IR ($CHCl_3$) cm^{-1}: 1348, 1166 (NSO_2). HRMS *m/z*: 453.0886 (Calcd for $C_{24}H_{23}NO_2S_3$: 453.0891). *Anal*. Calcd for $C_{24}H_{23}NO_2S_3$: C, 63.54; H, 5.11; N, 3.09. Found: C, 63.54; H, 5.10; N, 3.04.

5-(Phenylsulfonyl)-5,6-dihydro-4*H*-thieno[3,4-*c*]pyrrole (**9c**)[4b]: Pale yellow crystals. mp 141—143 °C (Et_2O) [lit.[4b] mp 136—137°C]. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 4.41 (4H, br s), 6.89 (2H, s), 7.44—7.64 (3H), 7.83—7.92 (2H) (each m). IR ($CHCl_3$) cm^{-1}: 1350, 1170 (NSO_2). HRMS *m/z*: 265.0231 (Calcd for $C_{12}H_{11}NO_2S_2$: 265.0231). *Anal*. Calcd for $C_{12}H_{11}NO_2S_2$: C, 54.32; H, 4.18; N, 5.28. Found: C, 54.30; H, 4.18; N, 5.15.

(*Z*)-Tetrahydro-4-[(phenylthio)methyl]-3-[(phenylthio)methylidene]furan [(*Z*)-**7d**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 2.96—3.02 (2H, m), 3.14—3.20 (1H, m), 3.87 (1H, dd, *J*=9, 4 Hz), 4.04 (1H, dd, *J*=9, 5.5 Hz), 4.41 (1H, br dd, *J*=14.5, 2 Hz), 4.46 (1H, ddd, *J*=14.5, 2, 1.5 Hz), 6.21 (1H, td, *J*=2, 1.5 Hz), 7.19—7.38 (10H, m). NOE was observed between methylene-H (δ 3.14-3.20) and olefinic-H (δ 6.21) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 37.16, 44.38, 70.53, 73.32, 113.97, 126.51, 126.55, 128.79, 129.06, 129.09, 129.12, 129.80, 135.65, 135.74, 145.55. HRMS *m/z*: 314.0809 (Calcd for $C_{18}H_{18}OS_2$: 314.0799).

3,4-Bis[(phenylthio)methyl]-2,5-dihydrofuran (**8d**): Yellow crystals. mp 78—79°C (Et_2O). ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 3.27 (4H, br s), 4.65 (4H, br s), 7.17—7.34 (10H, m). HRMS *m/z*: 314.0792 (Calcd for $C_{18}H_{18}OS_2$: 314.0799). *Anal*. Calcd for $C_{18}H_{18}OS_2$: C, 68.75; H, 5.77. Found: C, 68.54; H, 5.71.

1*H*,3*H*-Thieno[3,4-*c*]furan (**9d**)[11b]: A yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 4.83 (4H, br s), 6.84 (2H, s). HRMS *m/z*: 126.0137 (Calcd for C_6H_6OS: 126.0139).

Sulfanyl Radical Reaction of Diyne 6a Using V-70 To a solution of diyne **6a** (0.14 ml, 1.09 mmol) in benzene (5 ml) was added at room temper-

ature a solution of thiophenol (0.11 ml, 1.09 mmol) and V-70 (168 mg, 0.55 mmol) in benzene (5 ml) under nitrogen atmosphere by a syringe pump (3 ml/h) over 1.7 h. After being stirred at room temperature for another hour, the reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane) afforded **10a** (37 mg, 17%), **8a** (17 mg, 5%) and (*E*)-**7a** (6.8 mg, 2%). The adduct **10a** was obtained as a 1 : 1 mixture of *E*/*Z*-isomers.

Sulfanyl Radical Reaction of Adduct 10a To a boiling solution of **10a** (25 mg, 0.12 mmol) in benzene (3 ml) under nitrogen atmosphere was added a solution of thiophenol (0.03 ml, 0.12 mmol) and AIBN (10 mg, 0.06 mmol) in benzene (3 ml) by a syringe pump (2 ml/h) over 1.5 h. After the reaction mixture was heated at reflux for an hour more, the reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane) afforded **7a** (21 mg, 55%) as a 2 : 1 mixture of *E*/*Z*-isomers.

Attempted Isomerization of *E*-*exo*-Olefin *E*-7a to *endo*-Olefin 8a under Radical Conditions A solution of (*E*)-**7a** (33.3 mg, 0.11 mmol), thiophenol (0.01 ml, 0.11 mmol) and AIBN (9 mg, 0.06 mmol) in benzene (5 ml) was refluxed under nitrogen atmosphere for 6 h. The reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane) afforded (*E*)-**7a** (21.3 mg, 64%) and (*Z*)-**7a** (2.3 mg, 7%). **8a** could not be detected.

Attempted Isomerization of *endo*-Olefin 8a to *E*-*exo*-Olefin *E*-7a under the Radical Conditions According to the procedure given for attempted isomerization of (*E*)-**7a**, reaction of **8a** (31 mg, 0.1 mmol) with thiophenol (0.01 ml, 0.1 mmol) in the presence of AIBN (8.2 mg, 0.05 mmol) recovered **8a** (23.3 mg, 75%). (*E*)-**7a** could not be detected.

Dimethyl 3-Butynyl-2-propynylpropanedioate (12b) To a stirred suspension of NaH (60% in oil) (263 mg, 6.57 mmol) in tetrahydrofuran (THF) (6 ml) was added dropwise a solution of dimethyl 3-butynylpropanedioate (1.10 g, 5.97 mmol)[10a,b] in THF (3 ml) under nitrogen atmosphere at room temperature. After being stirred at the same temperature for 20 min, a solution of propargyl chloride (0.46 ml, 5.97 mmol) in THF (3 ml) was added dropwise to the reaction mixture at the same temperature. The reaction mixture was stirred at reflux temperature for 17 h, then diluted with saturated aqueous $NaHCO_3$ and extracted with Et_2O. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (Et_2O/petroleum ether 4 : 1) afforded **12b** (1.23 g, 92%) as a yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.98 and 2.05 (each 1H, br t, J=2.5 Hz), 2.20—2.28 (2H, m), 2.33—2.41 (2H, m), 2.88 (2H, d, J=2.5 Hz), 3.77 (6H, s). IR ($CHCl_3$) cm^{-1}: 3308 (C≡CH), 1740 (COO). HRMS *m*/*z*: 222.0908 (Calcd for $C_{12}H_{14}O_4$: 222.0892).

***N*-(3-Butynyl)-4-methyl-*N*-(2-propynyl)benzenesulfonamide (12c)** To a solution of the *N*-(2-propynyl)-*p*-toluenesulfonamide (1.76 g, 8.4 mmol)[12c,d] in THF (8 ml) was added 3-butyn-1-ol (1 ml, 12.5 mmol) and triphenylphosphine (2.2 g, 8.4 mmol) under argon atmosphere at room temperature. Then, diethyl azodicarboxylate (DEAD) (40% in toluene) was added dropwise. After being stirred for 2 h at room temperature, the solvent was removed under reduced pressure and the residue was purified by flash column chromatography (hexane/AcOEt 2 : 1) to afford **12c** (1.86 g, 85%) as a yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.01, 2.08 (each 1H, t, J=2.5 Hz), 2.43 (3H, s), 2.53 (2H, td, J=7, 2.5 Hz), 3.34 (2H, t, J=7 Hz), 4.21 (2H, d, J=2.5 Hz), 7.30, 7.74 (each 2H, br d, J=8 Hz). IR ($CHCl_3$) cm^{-1}: 3308 (C≡CH), 1350, 1161 (NSO_2). HRMS *m*/*z*: 261.0828 (Calcd for $C_{14}H_{15}NO_2S$: 261.0823).

Radical Cyclization of Diynes 12a—c (General Procedure) (Entries 1 and 2 in Table 2 and Chart 4) According to the procedure given for radical reaction of **6a**—**d**, the reaction of **12a**—**c** (1 mmol) with thiophenol (2 mmol) in the presence of AIBN (0.5 mmol) gave **13**—**15**, and **16** as shown in Table 2 and Chart 4.

Procedure Involving Addition of PhSH to a Mixture of 12c and PhSH (Entry 3 in Table 2) To a boiling solution of **12c** (100 mg, 0.38 mmol) and thiophenol (0.04 ml, 0.38 mmol) in benzene (5 ml) under nitrogen atmosphere was added a solution of thiophenol (0.04 ml, 0.38 mmol) and AIBN (27.3 mg, 0.17 mmol) in benzene (5 ml) by a syringe pump (2 ml/h) over 2.5 h. After being heated at reflux for a further 4 h, the reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane) afforded **13c** (25.5 mg, 14%), **14c** (46.6 mg, 25%), and **15c** (31.5 mg, 17%).

(*E*/*Z*)-[[[2-[(Phenylthio)methyl]cyclohexylidene]methyl]thio]benzene (**13a**): **13a** was formed as a 5 : 2 mixture of *E*/*Z*-isomers but a major product, (*E*)-**13a** was isolated by repeated purification by medium-pressure column chromatography (hexane).

(*E*)-[[[2-[(Phenylthio)methyl]cyclohexylidene]methyl]thio]benzene [(*E*)-**13a**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.52—1.72 (4H), 1.85—1.92 (2H) (each m), 2.33—2.45 (2H, m), 2.51 (1H, br quint., J=6 Hz), 3.02 (1H, dd, J=13, 7 Hz), 3.22 (1H, dd, J=13, 7.5 Hz), 5.95 (1H, br s), 7.14—7.38 (10H, m). NOE was observed between methylene-H (δ 3.02, 3.22) and olefinic-H (δ 5.95) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1350, 1170 (NSO_2). HRMS *m*/*z*: 326.1161 (Calcd for $C_{20}H_{22}S_2$: 326.1163). (*Z*)-**13a** was characterized by ^{1}H-NMR spectrum of a mixture of *E*/*Z*-isomers. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 3.10 (1H, dd, J=13, 9 Hz), 3.15 (1H, dd, J=13, 7 Hz), 6.00 (1H, br s), 7.14—7.38 (10H, m).

Dimethyl (*E*)-3-[(Phenylthio)methyl]-4-[(phenylthio)methylidene]-1,1-cyclohexanedicarboxylate [(*E*)-**13b**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 3.07 (1H, dd, J=12.5, 8.5 Hz), 3.16 (1H, dd, J=12.5, 7 Hz), 3.73, 3.75 (each 3H, s), 6.14 (1H, br s), 7.14—7.39 (10H, m). NOE was observed between methylene-H (δ 3.07, 3.16) and olefinic-H (δ 6.14) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1731 (COO). HRMS *m*/*z*: 442.1288 (Calcd for $C_{24}H_{26}O_4S_2$: 442.1273).

Dimethyl (*E*)-4-[(Phenylthio)methyl]-3-[(phenylthio)methylidene]-1,1-cyclohexanedicarboxylate [(*E*)-**14b**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.70 (1H, dtd, J=14, 7, 4.5 Hz), 2.01 (1H, td, J=9, 4.5 Hz), 2.08 (1H, ddd, J=14, 9, 4.5 Hz), 2.20 (1H, td, J=9, 4.5 Hz), 2.48 (1H, br dd, J=7, 4.5 Hz), 2.95, 3.00 (2H, ABq, J=14 Hz), 2.98 (1H, dd, J=12.5, 7 Hz), 3.21 (1H, dd, J=12.5, 7 Hz), 3.70, 3.72 (each 3H, s), 6.09 (1H, br s), 7.16—7.35 (10H, m). NOE was observed between methylene-H (δ 2.98, 3.21) and olefinic-H (δ 6.09) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1732 (COO). HRMS *m*/*z*: 442.1275 (Calcd for $C_{24}H_{26}O_4S_2$: 442.1273).

Dimethyl 3,4-Bis[(phenylthio)methyl]-3-cyclohexene-1,1-dicarboxylate (**15b**): A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.14 (2H, t, J=6 Hz), 2.25 (2H, br t, J=6 Hz), 2.72 (2H, s), 3.26, 3.28 (each 2H, br s), 3.72 (6H, s), 7.16—7.35 (10H, m). IR ($CHCl_3$) cm^{-1}: 1732 (COO). HRMS *m*/*z*: 442.1275 (Calcd for $C_{24}H_{26}O_4S_2$: 442.1273).

Dimethyl (*E*/*Z*)-2-[4-(Phenylthio)-3-butenyl]-2-propynylpropanedioate (**16b**): **16b** was obtained as a 3 : 2 mixture of *E*/*Z*-isomers. A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.01 (1H, t, J=2.5 Hz), 2.05—2.52 (4H, m), 2.85 (6/5H, d, J=2.5 Hz), 2.90 (4/5H, d, J=2.5 Hz), 3.74 and 3.75 (each 3H, s), 5.72—5.93 (1H, m), 6.20 (3/5H, br d, J=15 Hz), 6.22 (2/5H, br d, J=9 Hz), 7.10—7.38 (5H, m). IR ($CHCl_3$) cm^{-1}: 3309 (C≡CH). HRMS *m*/*z*: 332.1090 (Calcd for $C_{18}H_{20}O_4S$: 332.1082).

(*E*)-1-[(4-Methylphenyl)sulfonyl]-3-[(phenylthio)methyl]-4-[(phenylthio)-methylidene]piperidine [(*E*)-**13c**]: A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.97 (3H, s), 2.64—2.79 (2H, m), 6.02 (1H, br s), 7.11—7.82 (14H, m). IR ($CHCl_3$) cm^{-1}: 1353, 1161 (NSO_2). HRMS *m*/*z*: 481.1213 (Calcd for $C_{26}H_{27}NO_2S_3$: 481.1204).

(*Z*)-1-[(4-Methylphenyl)sulfonyl]-4-[(phenylthio)methyl]-3-[(phenylthio)-methylidene]piperidine [(*Z*)-**14c**]: A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.67 (1H, dtd, J=12.5, 7.5, 3.5 Hz), 2.00 (1H, br ddd, J=12.5, 8, 4 Hz), 2.37—2.46 (1H, m), 2.42 (3H, s), 2.88 (1H, dd, J=13, 8 Hz), 3.11 (1H, dd, J=13, 6.5 Hz), 3.12 (1H, ddd, J=12, 7.5, 4 Hz), 3.33 (1H, ddd, J=12, 8, 3.5 Hz), 3.74 (1H, d, J=13.5 Hz), 3.97 (1H, d, J=13.5 Hz), 6.13 (1H, br s), 7.15—7.35 (12H, m), 7.69 (2H, d, J=8 Hz). NOE was observed between methylene-H (δ 2.88, 3.11) and olefinic-H (δ 6.13) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1351, 1162 (NSO_2). HRMS *m*/*z*: 481.1214 (Calcd for $C_{26}H_{27}NO_2S_3$: 481.1204).

1,2,5,6-Tetrahydro-1-[(4-methylphenyl)sulfonyl]-3,4-bis[(phenylthio)-methyl]pyridine (**15c**): A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.32 (2H, br t, J=5.5 Hz), 2.46 (3H, s), 3.16 (2H, t, J=5.5 Hz), 3.19, 3.20 (each 2H, br s), 3.64 (2H, s), 7.11—7.76 (14H, m). IR ($CHCl_3$) cm^{-1}: 1343, 1162 (NSO_2). HRMS *m*/*z*: 481.1214 (Calcd for $C_{26}H_{27}NO_2S_3$: 481.1204).

(*E*/*Z*)-4-Methyl-*N*-[(4-phenylthio)-3-butenyl]-*N*-(2-propynyl)benzenesulfonamide (**16c**): **16c** was obtained as a 2 : 3 mixture of *E*/*Z*-isomers. A yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 2.04 (3/5H, t, J=2.5 Hz), 2.07 (2/5H, t, J=2.5 Hz), 2.43 (3H, s), 2.05—2.59 (2H, m), 3.30 (4/5H, br t, J=7 Hz), 3.40 (6/5H, br t, J=7 Hz), 4.15 (4/5H, d, J=2.5 Hz), 4.22 (6/5H, d, J=2.5 Hz), 5.77—5.88 (1H, m), 6.26 (2/5H, dt, J=14.5, 1 Hz), 6.32 (3/5H, dt, J=9, 1 Hz), 7.12—7.49 (7H), 7.70—7.78 (2H) (each m). IR ($CHCl_3$) cm^{-1}: 3307 (C≡CH), 1349, 1161 (NSO_2). HRMS *m*/*z*: 371.1022 (Calcd for $C_{20}H_{21}NO_2S_2$: 371.1014).

Attempted Isomerization of 14c to 15c under Radical Conditions According to the procedure given for attempted isomerization of (*E*)-**7a**, reaction of (*Z*)-**14c** (29.8 mg, 0.06 mmol) with thiophenol (0.006 ml, 0.06 mmol) in the presence of AIBN (3.1 mg, 0.03 mmol) recovered the (*Z*)-**14c** (22.1 mg, 74%). **15c** could not be detected.

Attempted Isomerization of 15c to 14c under Radical Conditions According to the procedure given for attempted isomerization of (*E*)-**7a**, reaction of **15**c (78.6 mg, 0.16 mmol) with thiophenol (0.02 ml, 0.16 mmol) in the presence of AIBN (8.3 mg, 0.08 mmol) recovered **15c** (22.1 mg, 74%). (*Z*)-**14c** could not be detected.

1,9-Bis(phenylthio)-1,8-nonadiene (18) According to the procedure given for sulfanyl radical cyclization of **6a**—**d**, reaction of **17** (100 mg, 0.83 mmol) with thiophenol (0.17 ml, 1.66 mmol) in the presence of AIBN (27.3 mg, 0.17 mmol) gave exclusively **18** (278.7 mg, 99%) as a mixture of *E*/*Z*-isomers. A yellow oil. ^{1}H-NMR (300 MHz, CDCl3) δ: 1.32—1.61 (6H, m), 2.02—2.31 (4H, m), 5.76—6.03, 6.09—6.22 (each 2H, m), 7.12—7.36 (10H, m). HRMS *m*/*z*: 340.1318 (Calcd for $C_{21}H_{24}S_2$: 340.1319).

(3S,5*R*)- and (3*R*,5*R*)-1-(Trimethylsilyl)-5-[(phenylmethoxy)methoxy]-1,7-octadiyn-3-ols (27, 28) To a stirred solution of trimethylsilylacetylide (1 ml, 7.07 mmol) in absolute THF (15 ml) was added *n*-BuLi (1.57 M in hexane) (4.5 ml, 7.07 mmol) under nitrogen atmosphere at −40 °C. After being stirred at the same temperature for 15 min, a solution of **26**[15] (547.3 mg, 2.36 mmol) in THF (15 ml) was added. The reaction mixture was stirred at the same temperature for 30 min, diluted with saturated aqueous NH_4Cl and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (hexane/AcOEt 3 : 1) afforded **27** (239 mg, 31%) and **28** (478 mg, 61%).

27: A yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 0.17 (9H, s), 2.05 (1H, t, *J*=2.5 Hz), 1.93—2.20 (2H, m), 2.42—2.68 (2H, m), 2.88 (1H, dd, *J*=6.5, 0.5 Hz), 4.08—4.21 (1H, m), 4.56—4.68 (1H, m), 4.66, 4.69 (2H, ABq, *J*=12 Hz), 4.87, 4.88 (2H, ABq, *J*=7 Hz), 7.24—7.48 (5H, m). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: −0.27, 24.68, 41.39, 59.69, 69.94, 70.59, 73.44, 80.12, 94.30, 106.14, 127.80, 128.38, 137.21. IR ($CHCl_3$) cm^{-1}: 3493 (OH), 3308 (C≡CH). HRMS *m*/*z*: 330.1649 (Calcd for $C_{19}H_{26}O_3Si$: 330.1651). $[\alpha]_D^{22}$ −33.9° (*c*=1.23, $CHCl_3$).

28: A yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 0.17 (9H, s), 2.05 (1H, t, *J*=2.5 Hz), 1.97—2.27 (2H, m), 2.44 (1H, dd, *J*=4.5, 2 Hz), 2.46—2.70 (2H, m), 3.95—4.08 (1H, m), 4.55—4.64 (1H, m), 4.64, 4.67 (2H, ABq, *J*=12 Hz), 4.83, 4.86 (2H, ABq, *J*=7 Hz), 7.22—7.43 (5H, m). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: −0.30, 24.59, 41.79, 60.75, 69.82, 70.58, 73.97, 80.16, 89.87, 93.90, 105.86, 127.68, 127.79, 128.33, 137.37. IR ($CHCl_3$) cm^{-1}: 3501 (OH), 3308 (C≡CH). HRMS *m*/*z*: 330.1657 (Calcd for $C_{19}H_{26}O_3Si$: 330.1651). $[\alpha]_D^{22}$ −32.1° (*c*=0.65, $CHCl_3$).

(3*S*,5*R*)-5-[(Phenylmethoxy)methoxy]-1,7-octadiyn-3-ol (29) To a stirred solution of **27** (202.2 mg, 0.61 mmol) in MeOH (6.1 ml) was added K_2CO_3 (305 mg, 2.2 mmol) under a nitrogen atmosphere at room temperature. After being stirred at the same temperature for 30 min, the reaction mixture was diluted with H_2O and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane/AcOEt 3 : 1) afforded **29** (158.1 mg, quant.) as a yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 2.04 (1H, t, *J*=2.5 Hz), 1.95—2.22 (2H, m), 2.47 (1H, d, *J*=2 Hz), 2.42—2.67 (2H, m), 3.00 (1H, d, *J*=7 Hz), 4.12—4.25 (1H, m), 4.57—4.69 (1H, m), 4.67, 4.68 (2H, ABq, *J*=12.5 Hz), 4.87, 4.90 (2H, ABq, *J*=7 Hz), 7.25—7.42 (m, 5H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: 24.53, 41.18, 59.21, 70.04, 72.90, 73.23, 79.96, 84.33, 94.21, 127.80, 128.39, 137.18. IR ($CHCl_3$) cm^{-1}: 3488 (OH), 3307 (C≡CH). HRMS *m*/*z*: 258.1256 (Calcd for $C_{16}H_{18}O_3$: 258.1256). $[\alpha]_D^{23}$ −55.7° (*c*=0.93, $CHCl_3$).

(3*R*,5*R*)-5-[(Phenylmethoxy)methoxy]-1,7-octadiyn-3-ol (30) According to the procedure given for the desilylation of **27**, **28** (34.1 mg, 0.1 mmol) was treated with K_2CO_3 (50 mg, 0.36 mmol) to afford **30** (26.7 mg, quant.) as a yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 2.05 (1H, t, *J*=2.5 Hz), 1.98—2.29 (2H, m), 2.47 (1H, d, *J*=4.5 Hz), 2.50 (1H, d, *J*=2.5 Hz), 2.44—2.69 (2H, m), 3.98—4.12 (1H, m), 4.57—4.66 (1H, m), 4.65, 4.67 (2H, ABq, *J*=12 Hz), 4.84, 4.88 (2H, ABq, *J*=7 Hz), 7.26—7.43 (5H, m). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: 24.47, 41.70, 60.05, 69.83, 70.67, 73.35, 73.58, 80.04, 84.14, 93.75, 127.68, 127.76, 128.30, 137.30. IR ($CHCl_3$) cm^{-1}: 3490 (OH), 3307 (C≡CH). HRMS *m*/*z*: 258.1266 (Calcd for $C_{16}H_{18}O_3$: 258.1256). $[\alpha]_D^{22}$ −90.4° (*c*=0.74, $CHCl_3$).

Mitsunobu Reaction of 28 To a stirred solution of **28** (55.1 mg, 0.17 mmol) in benzene (4 ml) was added benzoic acid (42.9 mg, 0.35 mmol) and PPh_3 (88.9 mg, 0.35 mmol) under nitrogen atmosphere at room temperature. Then, DEAD (40% in toluene) (148 mg, 0.34 mmol) was added dropwise to the reaction mixture. After being stirred at the same temperature for 5 h, the solvent was removed under reduced pressure. To a solution of the residue in MeOH (2 ml) was added K_2CO_3 (276 mg, 2 mmol) under nitrogen atmosphere at room temperature. After being stirred at the same temperature for 30 min, the reaction mixture was diluted with H_2O and was extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane/AcOEt 3 : 1) afforded **29** (40.7 mg, 93%) as a yellow oil which was identical with the sample prepared from **27**.

(3*S*,5*R*)-3-[[(1,1-Dimethylethyl)dimethylsilyl]oxy]-5-[(phenylmethoxy)-methoxy]-1,7-octadiyne (31a) To a solution of **29** (27 mg, 0.11 mmol) and 2,6-lutidine (0.025 ml, 0.21 mmol) in CH_2Cl_2 (2 ml) was added TBSOTf (0.03 ml, 0.13 mmol) under nitrogen atmosphere at 0 °C. After being stirred at the same temperature for 1 h, the reaction mixture was diluted with H_2O and was extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by medium-pressure column chromatography (hexane/AcOEt 20 : 1) afforded **31a** (38.9 mg, quant.) as a pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.11 and 0.16 (each 3H, s), 0.90 (9H, s), 2.04 (1H, t, *J*=2.5 Hz), 2.01—2.10 (2H, m), 2.41 (1H, d, *J*=2 Hz), 2.50 (1H, ddd, *J*=16.5, 4, 2.5 Hz), 2.66 (1H, ddd, *J*=16.5, 6, 2.5 Hz), 3.90—3.95 (1H, m), 4.54—4.57 (1H, m), 4.58, 4.76 (2H, ABq, *J*=12 Hz), 4.83, 4.86 (2H, ABq, *J*=7 Hz), 7.27—7.37 (5H, m). ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −1.97, −4.26, 18.13, 25.36, 25.81, 43.51, 59.28, 69.86, 70.50, 72.64, 73.46, 94.91, 127.74, 127.95, 128.44, 137.70. IR ($CHCl_3$) cm^{-1}: 3307 (C≡CH). HRMS *m*/*z*: 372.2122 (Calcd for $C_{22}H_{32}O_3Si$: 372.2119). $[\alpha]_D^{20}$ −72.9° (*c*=0.95, $CHCl_3$).

(3*R*,5*R*)-3-[[(1,1-Dimethylethyl)dimethylsilyl]oxy]-5-[(phenylmethoxy)-methoxy]-1,7-octadiyne (32) According to the procedure given for the silylation of **29**, **30** (71.5 mg, 0.28 mmol) was treated with TBSOTf (0.08 ml, 0.33 mmol) to afford **32** (103.1 mg, quant.) as a pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.12, 0.15 (each 3H, s), 0.90 (9H, s), 2.03 (1H, t, *J*=2.5 Hz), 2.03 (1H, ddd, *J*=13.5, 8, 4.5 Hz), 2.11 (1H, ddd, *J*=13.5, 8, 6 Hz), 2.42 (1H, dd, *J*=2, 0.5 Hz), 2.50 (1H, ddd, *J*=17, 4.5, 2.5 Hz), 2.66 (1H, ddd, *J*=17, 6, 2.5 Hz), 4.03—4.09 (1H, m), 4.60 (1H, ddd, *J*=8, 6, 2.5 Hz), 4.64, 4.69 (2H, ABq, *J*=12 Hz), 4.83, 4.87 (2H, ABq, *J*=7.5 Hz), 7.27—7.38 (5H, m). ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −5.06, −4.55, 18.17, 24.80, 25.76, 42.81, 60.38, 69.80, 70.45, 72.91, 73.18, 94.09, 127.71, 127.88, 128.42, 137.76. IR ($CHCl_3$) cm^{-1}: 3307 (C≡CH). HRMS *m*/*z*: 372.2110 (Calcd for $C_{22}H_{32}O_3Si$: 372.2119). $[\alpha]_D^{21}$ −86.1° (*c*=0.55, $CHCl_3$).

(3*S*,5*R*)-1,7-Octadiyn-3,5-Diol (33) To a solution of **29** (546 mg, 2.12 mmol) and thiophenol (0.44 ml, 4.34 mmol) in CH_2Cl_2 (5 ml) was added $BF_3\cdot OEt_2$ (1.1 ml, 8.48 mmol) under nitrogen atmosphere at 0 °C. After being stirred at the same temperature for 17 h, the solvent was removed under reduced pressure and the residue was purified by medium-pressure column chromatography (hexane → hexane/AcOEt 2 : 1) to afford **33** (243 mg, 83%) as a yellow oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 1.87 (2H, m), 2.09 (1H, t, *J*=2.5 Hz), 2.36—2.51 (2H, m), 2.52 (1H, d, *J*=2 Hz), 2.60 (1H, br d, *J*=3 Hz), 3.04 (1H, br d, *J*=5 Hz), 4.27—4.39 (1H, m), 4.65—4.74 (1H, m). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: 27.30, 41.44, 60.18, 67.33, 71.10, 73.33, 80.04, 83.97. IR ($CHCl_3$) cm^{-1}: 3452 (OH), 3306 (C≡CH). HRMS *m*/*z*: 138.0671 (Calcd for $C_8H_{10}O_2$: 138.0681). $[\alpha]_D^{22}$ −88.7° (*c*=0.62, $CHCl_3$).

(3*S*,5*R*)-3,5-Bis[[(1,1-dimethylethyl)dimethylsilyl]oxy]-1,7-octadiyne (31b) According to the procedure given for the silylation of **30**, **33** (243 mg, 1.76 mmol) was treated with TBSOTf (1 ml, 4.4 mmol) to afford **31b** (645 mg, quant.) as a pale yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 0.09, 0.10, 0.15, 0.17 (each 3H, s), 0.89, 0.90 (each 9H, s), 1.81—2.14 (2H, m), 1.99 (1H, t, *J*=2.5 Hz), 2.38 (2H, dd, *J*=6, 2.5 Hz), 2.42 (1H, d, *J*=2 Hz), 3.94—4.08 (1H, m), 4.52 (1H, ddd, *J*=8.5, 5, 2 Hz). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: 17.93, 18.05, 25.73, 27.61, 46.07, 59.29, 67.27, 70.24, 72.75, 80.89, 85.50. IR ($CHCl_3$) cm^{-1}: 3307 (C≡CH). HRMS *m*/*z*: 366.2419 (Calcd for $C_{20}H_{38}O_2Si_2$: 366.2410). $[\alpha]_D^{20}$ −78.0° (*c*=1.16, $CHCl_3$).

Sulfanyl Radical Addition–Cyclization Reaction of 31a To a boiling solution of the diyne **31a** (43.2 mg, 0.12 mmol) in benzene (5 ml) under nitrogen atmosphere was added a solution of thiophenol (0.016 ml, 0.15 mmol) and AIBN (9.53 mg, 0.06 mmol) in benzene (5 ml) by a syringe pump (2 ml/h) over 2.5 h. After being heated at reflux for a further 3.5 h, the reaction mixture was neutralized with 5% KOH and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. The repeated purification of the residue by medium-pressure column chromatography (hexane → hexane/AcOEt 30 : 1) afforded **34a** (13.1 mg, 19%), **35a** (10.3 mg, 15%), and **36a** (2 mg, 3%).

[2*R*-(1*E*,2α,3α,5β)]-[[[3-[[(1,1-Dimethylethyl)dimethylsilyl]oxy]-5-

[(phenylmethoxy)methoxy]-2-[(phenylthio)methyl]-cyclohexylidene]-methyl]-thio]benzene (**34a**): A pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: −0.07, 0.03 (each 3H, s), 0.87 (9H, s), 1.81 (1H, ddd, J=13, 9.5, 3 Hz), 1.97 (1H, br dt, J=13, 4.5 Hz), 2.24 (1H, br dd, J=13.5, 9.5 Hz), 2.45 (1H, br td, J=7, 4.5 Hz), 3.02 (1H, br dd, J=13.5, 4.5 Hz), 3.04 (1H, dd, J=13, 7 Hz), 3.16 (1H, dd, J=13, 7 Hz), 4.03 (1H, tt, J=9.5, 4.5 Hz), 4.12 (1H, br td, J=4.5, 3 Hz), 4.61 (2H, s), 4.77, 4.81 (2H, ABq, J=7 Hz), 6.07 (1H, s), 7.15—7.35 (15H, m). NOE was observed between methylene-H (δ 3.04, 3.16) and olefinic-H (δ 6.07) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −4.83, −4.77, 17.98, 25.74, 33.73, 34.65, 37.07, 51.61, 69.40, 70.67, 71.93, 92.90, 119.44, 125.77, 126.11, 127.61, 127.87, 128.18, 128.38, 128.88, 128.99, 129.22, 136.27, 136.92, 137.88, 140.99. HRMS *m/z*: 592.2517 (Calcd for $C_{34}H_{44}O_3S_2Si$: 592.2501).

[2*S*-(2α,4β,6ξ)]-[[[2-[[(1,1-Dimethylethyl)dimethylsilyl]oxy]-4-[(phenylmethoxy)methoxy]-6-[(phenylthio)methyl]cyclohexylidene]methyl]-thio]benzene (**35a**): A pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.08, 0.14 (each 3H, s), 0.83 (9H, s), 2.26 (1H, br dd, J=12.5, 3 Hz), 2.50 (1H, br dd, J=12.5, 3 Hz), 2.88—2.93 (2H, m), 3.23 (1H, br dd, J=15, 4 Hz), 3.26 (1H, br dd, J=13, 7.5 Hz), 3.38 (1H, br dd, J=13, 7.5 Hz), 4.18—4.26 (1H, m), 4.61, 4.62 (2H, ABq, J=11.5 Hz), 4.81, 4.84 (2H, ABq, J=7 Hz), 5.10 (1H, br t, J=3 Hz), 5.98 (1H, br s), 7.12—7.38 (15H, m). ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −5.07, −4.65, 17.91, 25.76, 30.06, 36.59, 40.27, 41.68, 67.63, 69.37, 71.80, 93.22, 114.92, 126.14, 127.86, 128.43, 128.86, 128.91, 129.04, 129.46, 136.34, 136.65, 137.94, 145.60. HRMS *m/z*: 592.2513 (Calcd for $C_{34}H_{44}O_3S_2Si$: 592.2501).

[3*S*-(3α,5β)]-3-[[(1,1-Dimethylethyl)dimethylsilyl]oxy]-5-[(phenylmethoxy)methoxy]-1,2-bis[(phenylthio)methyl]-1-cyclohexene (**36a**): A pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.02, 0.08 (each 3H), 0.87 (9H, s), 1.68 (1H, ddd, J=13, 11, 4 Hz), 2.00 (1H, br dd, J=12, 9 Hz), 2.06 (1H, br dtd, J=13, 4, 1.5 Hz), 2.74 (1H, br dd, J=12, 4 Hz), 2.95 (1H, d, J=12.5 Hz), 3.15 (1H, d, J=12.5 Hz), 3.39 (1H, d, J=12.5 Hz), 3.43 (1H, d, J=12.5 Hz), 4.06—4.12 (1H, m), 4.52 (1H, br t, J=4 Hz), 4.63 (2H, s), 4.82, 4.83 (2H, ABq, J=7 Hz), 7.20—7.38 (15H, m). ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −4.76, −4.42, 17.96, 25.81, 33.31, 35.18, 37.49, 38.49, 66.94, 69.33, 69.51, 93.09, 126.74, 127.15, 127.62, 127.85, 128.40, 128.76, 128.84, 131.15, 131.48, 132.13, 135.49, 136.18, 137.90, 141.05. HRMS *m/z*: 592.2508 (Calcd for $C_{34}H_{44}O_3S_2Si$: 592.2501).

Sulfanyl Radical Addition–Cyclization Reaction of 31b According to the procedure given for the radical reaction of **31a**, reaction of **31b** (197 mg, 0.54 mmol) with thiophenol (0.11 ml, 1.08 mmol) in the presence of AIBN (44 mg, 0.27 mmol) afforded **34b** (120 mg, 38%) and the mixture of **35b** and **36b** (**35b** : **36b**=1 : 1) (89 mg, 28%).

[2*R*-(1*E*,2α,3α,5β)]-[[[3,5-Bis[[(1,1-dimethylethyl)dimethylsilyl]oxy]-2-[(phenylthio)methyl]cyclohexylidene]methyl]thio]benzene (**34b**): A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.04, 0.05 (each 6H, s), 0.08 (18H, s), 1.74 (1H, ddd, J=13, 10, 3 Hz), 1.84 (1H, dt, J=13, 3 Hz), 2.12 (1H, ddd, J=13.5, 10, 1 Hz), 2.46 (1H, td, J=7, 3 Hz), 2.92 (1H, ddd, J=13.5, 4.5, 1 Hz), 3.04 (1H, dd, J=13, 7 Hz), 3.12 (1H, dd, J=13, 7 Hz), 4.02 (1H, tdd, J=10, 4.5, 3 Hz), 4.12 (1H, dd, J=7, 3 Hz), 6.02 (1H, s), 7.11—7.34 (10H, m). NOE was observed between methylene-H (δ 3.04, 3.12) and olefinic-H (δ 6.02) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −4.88, 25.70, 25.88, 29.70, 34.72, 36.76, 51.48, 57.26, 70.78, 118.73, 125.59, 126.04, 127.65, 128.03, 128.10, 128.81, 128.95, 129.17, 136.30, 137.21, 142.45. HRMS *m/z*: 586.2816 (Calcd for $C_{32}H_{50}O_2S_2Si_2$: 586.2791). $[\alpha]_D^{20}$ −46.7° (*c*=2.26, $CHCl_3$).

[2*S*-(2α,4β,6ξ)]-[[[2,4-Bis[[(1,1-dimethylethyl)dimethylsilyl]oxy]-6-[(phenylthio)methyl]cyclohexylidene]methyl]thio]benzene (**35b**) and [3*S*-(3α,5β)]-3,5-Bis[[(1,1-dimethylethyl)dimethylsilyl]oxy]-1,2-bis[(phenylthio)methyl]-1-cyclohexene (**36b**): ^{1}H-NMR (300 MHz) δ: 2.52 (1/2H, m (**35b**)), 2.58 (1/2H, m (**35b**)), 2.88 (1/2H, br d, J=12 Hz (**36b**)), 3.15 (1/2H, br d, J=12 Hz (**36b**)), 3.37 (1/2H, br d, J=12 Hz, (**36b**)), 3.41 (1/2H, br d, J=12 Hz (**36b**)), 4.02—4.12 (1/2H, m (**36b**)), 4.18—4.28 (1/2H, m (**35b**)), 4.51 (1/2H, br t, J=3 Hz (**36b**)), 5.06 (1/2H, br t, J=3 Hz (**35b**)), 5.96 (1/2H, br s, (**35b**)).

(*E*)- and (*Z*)-[[(2-Methylenecyclohexylidene)methyl]sulfinyl]benzenes (42, 45) To a stirred solution of **13a** (*E* : *Z*=5 : 2) (2.3 g, 7 mmol) in CH_2Cl_2 (70 ml) was added dropwise mCPBA (70%, assay) (3.47 g, 14 mmol) in CH_2Cl_2 (140 ml) under nitrogen atmosphere at 0 °C. After being stirred at the same temperature for 30 min, the reaction mixture was neutralized with saturated aqueous $NaHCO_3$ and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure to give the crude sulfoxide. A solution of the crude sulfoxide in toluene (130 ml) was heated at reflux under nitrogen atmosphere for 6 h. The solvent was removed under reduced pressure and purification of the residue by short column chromatography (hexane → hexane/AcOEt 5 : 1 → AcOEt) afforded **42** (418 mg, 26%) and **45** (167 mg, 10%).

42: A colorless oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.65—1.72 (1H, m), 1.72—1.87 (3H, m), 2.28—2.38 (2H, m), 2.64—2.70 (1H, m), 2.90—2.96 (1H, m), 4.78 (1H, dd, J=2.5, 1 Hz), 4.92 (1H, br d, J=1 Hz), 6.21 (1H, s), 7.43—7.54 (3H), 7.57—7.62 (2H) (each m). NOE were observed between 4-Hax (δ 1.65—1.72) and 6-Hax (δ 2.64—2.70), and between olefinic-H (δ 4.92) adjacent to 2-position and olefinic-H (δ 6.21) adjacent to 1-position in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 26.07, 26.26, 30.92, 34.93, 111.70, 124.07, 129.26, 129.31, 130.46, 144.98, 147.67, 153.95. IR ($CHCl_3$) cm^{-1}: 1028 (SO). HRMS *m/z*: 232.0900 (Calcd for $C_{14}H_{16}OS$: 232.0922).

45: A colorless oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.68—1.84 (4H, m), 2.28—2.51 (4H, m), 5.11 (1H, br s), 5.20 (1H, dd, J=3, 1.5 Hz), 6.10 (1H, s), 7.45—7.56 (3H), 7.65—7.68 (2H) (each m). NOE was observed between olefinic-H (δ 5.20) and ArH (δ 7.45—7.56) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 27.04, 27.10, 36.36, 37.39, 48.09, 115.25, 124.63, 129.15, 129.26, 129.66, 130.57, 144.35. IR ($CHCl_3$) cm^{-1}: 1020 (SO). HRMS *m/z*: 232.0909 (Calcd for $C_{14}H_{16}OS$: 232.0922).

Introduction of Alkoxycarbonyl Group to α-Position in 42 (Table 4). [Table 4, Entry 5] To a solution of **42** (99 mg, 0.43 mmol) in THF (4.3 ml) was added MeLi (1.1 M solution in Et_2O) (0.58 ml, 0.64 mmol) under nitrogen atmosphere at −100 °C. After being stirred at the same temperature for 15 min, ClCOOMe (0.08 ml, 0.85 mmol) was added to the reaction mixture. After further stirring at the same temperature for 15 min, the reaction mixture was diluted with saturated aqueous NH_4Cl and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (hexane/AcOEt 2 : 1) afforded **43a** (44 mg, 36%), **44a** (22 mg, 18%) and **45** (3 mg, 3%).

Methyl (*E*)-(2-Methylenecyclohexylidene)(phenylsulfinyl)acetate (**43a**): A pale yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.67—1.98 (4H, m), 2.40 (2H, br t, J=6 Hz), 2.71—2.87 (1H, m), 2.88—3.06 (1H, m), 3.48 (3H, s), 4.85, 4.87 (each 1H, br s), 7.44—7.64 (5H, m). IR ($CHCl_3$) cm^{-1}: 1724 (COO). HRMS *m/z*: 290.0100 (Calcd for $C_{16}H_{18}O_3S$: 290.0075).

Methyl (*Z*)-(2-Methylenecyclohexylidene)(phenylsulfinyl)acetate (**44a**): A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.71—1.81 (2H, m), 1.81—1.87 (1H, m), 1.87—1.95 (1H, m), 2.28—2.43 (2H, m), 2.53—2.59 (1H, m), 2.67—2.73 (1H, m), 3.43 (3H, s), 5.30 (1H, br d, J=1 Hz), 5.34 (1H, br s), 7.43—7.53 (3H), 7.58—7.60 (2H) (each m). NOE was observed between olefinic-H (δ 5.34) and Ar-H (δ 7.43—7.53) in NOESY spectroscopy. HRMS *m/z*: 290.0086 (Calcd for $C_{16}H_{18}O_3S$: 290.0075).

[Table 4, Entry 4] To a solution of **42** (31 mg, 0.13 mmol) in THF (2 ml) was added *tert*-BuLi (1.54 M solution in *n*-pentane) (0.12 ml, 0.19 mmol) under nitrogen atmosphere at −100 °C. After being stirred at the same temperature for 30 min, ClCOOMe (0.02 ml, 0.26 mmol) was added. The reaction mixture was stirred at the same temperature for 15 min, diluted with saturated aqueous NH_4Cl, and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (hexane/AcOEt 2 : 1) afforded methyl (*E*)-(2-methylenecyclohexylidene)[(1,1-dimethylethyl)sulfinyl]acetate (**46**) as a pale yellow oil. (5.6 mg, 16%). ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.34 (9H, s), 1.52—1.88 (4H, m), 2.28—2.44 (3H, m), 2.72—2.86 (1H, m), 3.70 (3H, s), 4.88, 4.90 (each 1H, br s). IR ($CHCl_3$) cm^{-1}: 1727 (COO), 1037 (SO). HRMS *m/z*: 270.1260 (Calcd for $C_{14}H_{22}O_3S$: 270.1290).

[Table 4, Entry 6] To a solution of **42** (215 mg, 0.93 mmol) in THF (9 ml) was added MeLi (1.1 M solution in Et_2O) (1.22 ml, 1.4 mmol) under nitrogen atmosphere at −100 °C. After being stirred at the same temperature for 15 min, NCCOOEt (0.18 ml, 1.86 mmol) was added. The reaction mixture was further stirred at the same temperature for 15 min, diluted with saturated aqueous NH_4Cl, and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (hexane/AcOEt 2 : 1) afforded **43b** (139 mg, 49%) and **44b** (36 mg, 13%).

Ethyl (*E*)-(2-Methylenecyclohexylidene)(phenylsulfinyl)acetate (**43b**): A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.04 (3H, t, J=7 Hz), 1.69—1.77 (1H, m), 1.77—1.97 (3H, m), 2.36—2.46 (2H, m), 2.78 (1H, ddd, J=13.5, 9, 4.5 Hz), 2.98 (1H, br ddd, J=13.5, 7, 4 Hz), 3.85—4.05 (2H, m), 4.86 (2H, br s), 7.44—7.52 (3H), 7.78—7.61 (2H) (each m). NOE was observed between CH_3 (δ 1.04) and olefinic-H (δ 4.86), and between 4-Hax (δ 1.69—1.77) and 6-Hax (δ 2.78) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1720 (COO), 1041 (SO). HRMS *ms/z*: 304.1138 (Calcd for $C_{17}H_{20}O_3S$: 304.1133).

Ethyl (*Z*)-(2-Methylenecyclohexylidene)(phenylsulfinyl)acetate (**44b**): A yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.01 (3H, t, J=7 Hz), 1.64—1.96 (4H, m), 2.18—2.47 (2H, m), 2.47—2.61 (2H, m), 3.80—4.00 (2H, m), 5.30 and 5.34 (each 1H, br s), 7.41—7.56 (3H), 7.56—7.66 (2H) (each, m). IR ($CHCl_3$) cm^{-1}: 1720 (COO), 1043 (SO). HRMS *m/z*: 304.1129 (Calcd for $C_{17}H_{20}O_3S$: 304.1133).

[3*S*-(1*E*,3α,5β)]-[[[3,5-Bis[[(1,1-dimethylethyl)dimethylsily]oxy]-2-methylenecyclohexylidene]methyl]sulfinyl]benzene (38) According to the procedure given for the oxidation and subsequent pyrolysis of **13a**, **34b** (132 mg, 0.23 mmol) was converted into **38** (42 mg, 37%) *via* disulfoxide **37**. A yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: −0.09, 0.02, 0.08, 0.12 (each 3H, s), 0.81, 0.91 (each 9H, s), 0.83—1.91 (2H, m), 2.76—2.88 (2H, m), 4.28 (1H, ddd, J=10.5, 6.5, 4 Hz), 4.51 (1H, br dd, J = 6, 5 Hz), 5.00, 6.23 (each 1H, br s), 6.23 (1H, t, J=1 Hz), 7.42—7.58 (5H, m). NOE was observed between olefinic-H (δ 5.00) adjacent to 1-position and olefinic-H (δ 6.23) adjacent to 2-position in NOESY spectroscopy. ^{13}C-NMR (50 MHz, $CDCl_3$) δ: −5.26, −5.02, −4.09, 17.93, 18.02, 25.53, 25.69, 39.04, 43.43, 66.60, 70.45, 111.16, 123.94, 129.14, 130.32, 132.63, 144.78, 149.63. IR ($CHCl_3$) cm^{-1}: 1085 (SO). HRMS *m/z*: 492.2546 (Calcd for $C_{26}H_{44}O_3SSi_2$: 492.2550). $[\alpha]_D^{23}$ −6.0° (*c*=0.69, $CHCl_3$).

Introduction of Ethoxycarbonyl Group to α-Position in 38 To a solution of **38** (34.5 mg, 0.07 mmol) in THF (0.7 ml) was added MeLi (1.1 M solution in Et_2O) (0.09 ml, 0.11 mmol) under nitrogen atmosphere at −100 °C. After being stirred at the same temperature for 15 min, NCCOOEt (0.013 ml, 0.14 mmol) was added. The reaction mixture was stirred at the same temperature for another 15 min, diluted with saturated aqueous NH_4Cl and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. Purification of the residue by flash column chromatography (hexane/AcOEt 3 : 1) afforded (*E*)-**39** (16.8 mg, 43%) and (*Z*)-**39** (6.9 mg, 18%).

Ethyl [3*S*-(1*E*,3α,5β)]-[3,5-Bis[[(1,1-dimethylethyl)dimethylsily]oxy]-2-methylenecyclohexylidene](phenylsulfinyl)acetate [(*E*)-**39**]: A yellow solid. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.02, 0.06, 0.09, 0.13 (each 3H, s), 0.88, 0.92 (each 9H, s), 1.05 (3H, t, J=7 Hz), 1.77 (1H, ddd, J=12, 9, 2.5 Hz), 2.03 (1H, dddd, J=12, 6, 5, 1.5 Hz), 2.63 (1H, dd, J=13.5, 3 Hz), 3.09 (1H, ddd, J=13.5, 5.5, 1.5 Hz), 3.93—4.06 (2H, m), 4.31—4.35 (1H, m), 4.61—4.66 (1H, m), 4.96, 5.11 (each 1H, t, J=1.5 Hz), 7.42—7.49 (3H), 7.55—7.58 (2H) (each m). NOE was observed between 4-Hax (δ 1.77) and 6-Hax (δ 2.63), and between Me (δ 1.05) and olefinic-H (δ 5.11) in NOESY spectroscopy. IR ($CHCl_3$) cm^{-1}: 1723 (COO), 1088 (SO). HRMS *m/z*: 564.2756 (Calcd for $C_{29}H_{48}O_5SSi_2$: 564.2761). $[\alpha]_D^{22}$ −74.5° (*c*=0.80, $CHCl_3$).

Ethyl [3*S*-(1*Z*,3α,5β)]-[3,5-Bis[[(1,1-dimethylethyl)dimethylsily]oxy]-2-methylenecyclohexylidene](phenylsulfinyl)acetate [(*Z*)-**39**]: A pale yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.00, 0.06, 0.07, 0.09 (each 3H, s), 0.86, 0.92 (each 9H, s), 0.93 (3H, t, J=7 Hz), 1.73 (1H, dddd, J=13, 11, 2.5, 2 Hz), 2.14 (1H, br dt, J=13, 5 Hz), 2.35 (1H, dd, J=13.5, 3 Hz), 3.02 (1H, ddd, J=13.5, 3.5, 2 H), 3.78—3.86 (1H, m), 3.88—3.98 (1H, m), 4.28—4.32 (1H, m), 4.60—4.64 (1H, m), 5.59—5.61 (2H, m), 7.37—7.45 (3H), 7.57—7.55 (2H) (each m). NOE was observed between 4-Hax (δ 1.73) and 6-Hax (δ 2.35), and between olefinic-H (δ 5.59—5.61) and Ar-H (δ 7.37—7.45) in NOESY spectroscopy. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −5.29, −4.87, −3.70, 14.02, 17.82, 25.54, 25.71, 32.19, 40.95, 61.98, 63.16, 65.51, 124.71, 127.14, 128.39, 128.73, 129.12, 130.59, 131.00, 132.44, 136.34. IR ($CHCl_3$) cm^{-1}: 1718 (COO), 1085 (SO). HRMS *m/z*: 564.2773 (Calcd for $C_{29}H_{48}O_5SSi_2$: 564.2761). $[\alpha]_D^{24}$ −39.2° (*c*=0.74, $CHCl_3$).

Desulfurization of (*E*)-39 To a solution of (*E*)-**39** (15.7 mg, 0.03 mmol) in Et_2O (1 ml) was added *tert*-BuLi (1.54 M in *n*-pentane) (0.04 ml, 0.05 mmol) under nitrogen atmosphere at −100 °C, and several seconds later MeOH (1 ml) was added as described in the literature.[18] The reaction mixture was diluted with H_2O and extracted with $CHCl_3$. The organic phase was washed with H_2O, dried over $MgSO_4$, and concentrated under reduced pressure. The repeated purification of the residue by medium-pressure column chromatography (hexane/AcOEt 50 : 1→hexane/AcOEt 7 : 1) afforded (*Z*)-**40** (1.6 mg, 13%), (*E*)-**40** (0.7 mg, 6%), and **41** (5.2 mg, 52%).

Ethyl [3*S*-(1*Z*,3α,5β)]-[3,5-Bis[[(1,1-dimethylethyl)dimethylsily]oxy]-2-methylenecyclohexylidene]acetate [(*Z*)-**40**]: A colorless oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.03, 0.07 (each 6H, s), 0.85, 0.88 (each 9H, s), 1.21 (3H, t, J=7 Hz), 1.74 (1H, br ddd, J=12, 9, 3 Hz), 1.91 (1H, br dt, J=12, 5.5 Hz), 2.23 (1H, br dd, J=13, 5.5 Hz), 2.40 (1H, br d, J=13 Hz), 4.04—4.13 (2H, m), 4.20—4.24 (1H, m), 4.51 (1H, br dd J=9, 3 Hz), 5.00, 5.17 (each 1H, br s), 5.61 (1H, s). ^{13}C-NMR (125 MHz, $CDCl_3$) δ: −5.21, −4.91, 14.12, 18.03, 18.26, 25.71, 25.78, 44.68, 46.13, 59.74, 67.38, 70.88, 110.66, 117.67, 147.36, 152.93, 166.03. IR ($CHCl_3$) cm^{-1}: 1717 (COO). HRMS *m/z*: 440.2777 (Calcd for $C_{23}H_{44}O_4Si_2$: 440.2776). $[\alpha]_D^{22}$ −38.1° (*c*=0.11, EtOH) [lit.[14f] $[\alpha]_D^{25}$ −36.9° (*c*=0.3, EtOH)]. These spectral data are identical with those reported.[14f]

Ethyl [3*S*-(1*E*,3α,5β)]-[3,5-Bis[[(1,1-dimethylethyl)dimethylsily]oxy]-2-methylenecyclohexylidene]acetate [(*E*)-**40**]: A colorless oil. ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 0.06, 0.07 (each 6H, s), 0.87, 0.91 (each 9H, s), 1.27 (3H, t, J=7.5 Hz), 1.77 (1H, ddd, J=12, 9, 2.5 Hz, 1.98 (1H, br d, J=12 Hz), 2.66 (1H, br d, J=14 Hz), 3.39 (1H, br d, J=14 Hz), 4.09—4.16 (2H, m), 4.24—4.27 (1H,), 4.56—4.60 (1H, m), 5.07, 5.09, 5.91 (each 1H, s). These spectral data are identical with those reported.[14f]

[(1,1-Dimethylethyl)sulfinyl]benzene (**41**): A yellow oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.18 (9H, s), 7.45—7.54 (3H), 7.54—7.67 (2H) (each m). IR ($CHCl_3$) cm^{-1}: 1032 (SO). HRMS *m/z*: 182.0764 (Calcd for $C_{10}H_{14}OS$: 182.0765). These spectral data are identical with those reported.[18]

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