Pergamon

Tetrahedron, Vol. 53, No. 12, pp. 4291-4308, 1997

0040-4020/97 $17.00 + 0.00

PII: S0040-4020(97)00156-7

Generation and Intramolecular Cyclization of α-Phenylsulfenyl and α-Alkylsulfenyl Radicals

Yeun-Min Tsai,* Fu-Chang Chang, Jimin Huang, Chi-Lung Shiu, Chai-Lin Kao and Jyh-Shiunn Liu

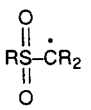
Department of Chemistry, National Taiwan University, Taipei, Taiwan 106, Republic of China

Abstract: α-Phenylsulfenyl radicals are generated by the reaction of diphenyl dithioacetals or phenyl α-chlorosulfides with tributyltin hydride. Alkyl phenyl dithioacetals react selectively with tributyltin hydride to give α-alkylsulfenyl radicals. 5-*Exo*-type of intramolecular cyclizations of these radicals are studied. The cyclization is most successful when the olefin is terminally substituted with an ester group. The *cis/trans* ratio of the cyclized product varies according to the reaction rates. With a faster cyclization, *cis*-isomer is the major product. A slower cyclization gives more *trans*-product.

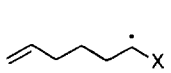
Radicals which carry α-sulfur functionalities (**1–3**) are potentially useful reactive intermediates. Because of the rich chemistry that organosulfur compounds exhibit,[1] the combination of sulfur functionalities with radicals will greatly enhance their synthetic utilities. At the beginning of our research in this area, we concentrated on the intramolecular cyclizations of this type of radicals. Although there were some reports about the chemistry of α-sulfenyl (**1**)[1a,2] and α-sulfonyl (**3**)[3] radicals at the time we started, a systematic model study of the substituted 5-hexenyl radical systems such as **4–6** was lacking. Herein, we wish to report our full investigation about α-sulfenyl radical **4**.[2a]

1

2



3

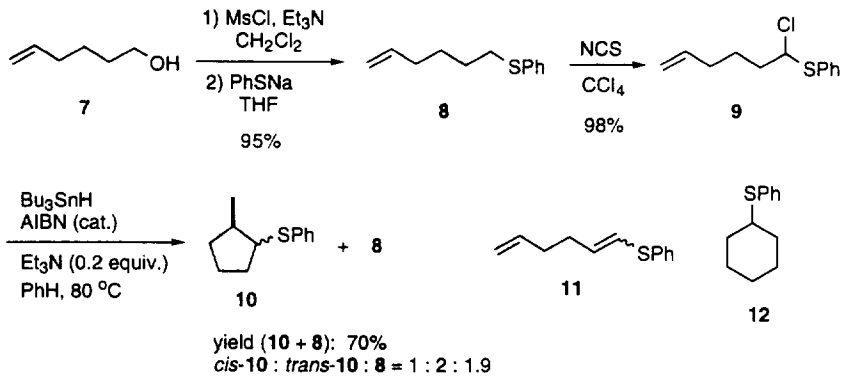


4 X = SR
5 X = SOR
6 X = SO_2R

RESULTS AND DISCUSSION

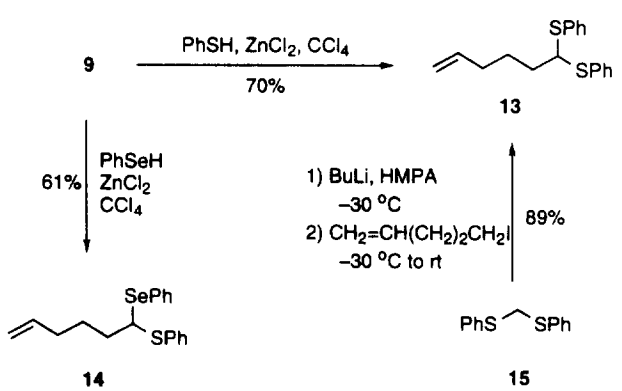
It is well known that α-chlorosulfide can be prepared from the corresponding sulfide.[4] In principle, reaction of α-chlorosulfide with tributyltin hydride should generate the desired α-sulfenyl radical. To test this possibility, we first prepared sulfide **8**[5] (95%) from alcohol **7** (Scheme 1). Treatment of **8** with NCS in carbon tetrachloride gave cleanly chloride **9** in 98% yield. This chloride was moisture sensitive and decomposed

Scheme 1



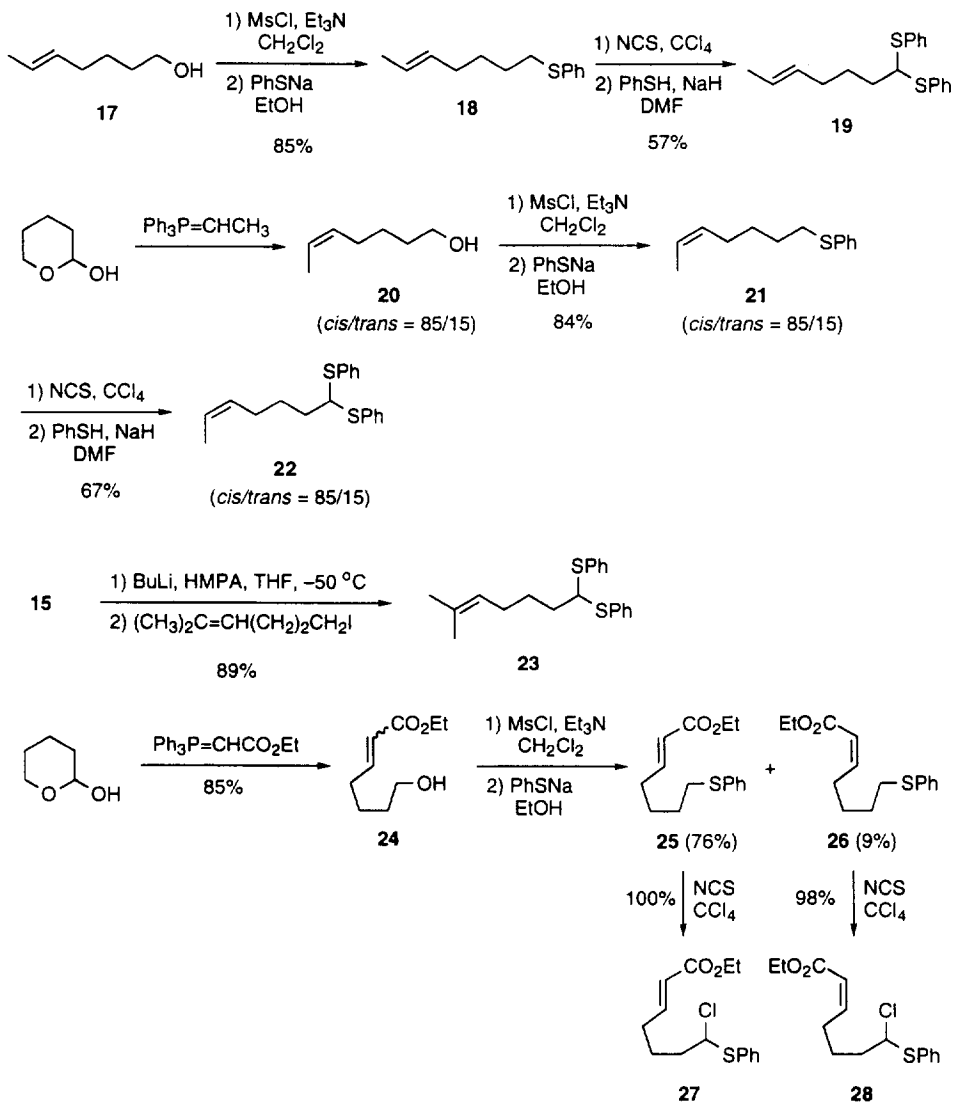
during silica gel column chromatography.[4] Therefore, the crude chloride **9** was used directly in the cyclization reaction. The cyclization reaction was performed by slow addition (6 h) of a benzene solution of tributyltin hydride and catalytic amount of AIBN to a refluxing benzene solution of **9**. The final concentration of **9** was controlled at 0.05 M. A mixture of cyclization product **10** and reduction product **8** was obtained. In addi-tion, a diene sulfide **11** was also isolated in appreciable amount. The formation of this diene side product could be avoided by the addition of 0.2 equivalent of triethylamine in the solution of **9** during cyclization. Although the origin of **11** was not clear, we suspected that due to the moisture sensitive nature of **9** there might be some hydrochloric acid present which catalyzed the dehydrochlorination of **9** to give **11**. This explained the finding that triethylamine inhibited the formation of diene **11**. In this way, we obtained a mixture of **10** and **8** in 70% yield. The ratio of *cis*-**10** : *trans*-**10** : **8** was determined by ^{1}H NMR integration as 1/2/1.9. The stereochemistry of **10** was determined by alternative synthesis of *cis*- and *trans*-**10** from the reaction of *trans*- and *cis*-2-methylcyclopentanol, respectively, with *N*-phenylsulfenylsuccinimide and tributylphosphine.[6] Similarly, we also synthesized cyclohexyl phenyl sulfide **12** from cyclohexanol. Gas chromatographic analysis of the cyclization product mixture showed that there was at most 2% of **12** present.

Scheme 2



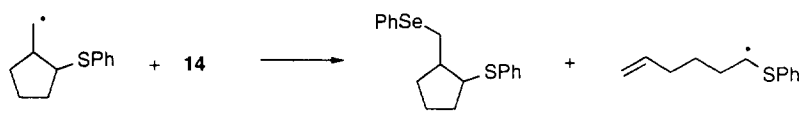
In attempt to increase the extent of cyclization, we performed the reaction in a more dilute condition (0.01 M). Unfortunately, only diene **11** was obtained in 83% yield even in the presence of 1 equivalent of triethylamine. We therefore decided to examine the possibility of using the less moisture sensitive dithioacetal[2g,7] **13** and selenide **14** for our purpose (Scheme 2). Dithioacetal **13** was synthesized from **9** in 70% yield by reacting **9** with thiophenol in the presence of zinc chloride.[8] However, this method sometimes gave six-membered ring side product derived from cationic π-cyclization. Separation of this side product was difficult. Similarly, selenide **14** was synthesized in 61% yield. Alternatively, alkylation of the anion of **15**[9] with 5-iodopentene[10] in the presence of HMPA also afforded **13** in better yield (89%).

Scheme 3



The reaction of **13** with tributyltin hydride under the same condition described above (0.05 M) without triethylamine gave 84% of a mixture of *cis*-**10**, *trans*-**10** and **8** in a ratio of 1/1.7/1.7, respectively. None of the diene sulfide **11** was observed. Under more dilute condition (0.01 M), however, no reaction occurred and **13** was recovered. This indicated that although at higher concentration α-sulfenyl radical could be generated from dithioacetal **13**, the reactivity of the sulfide towards tin radical was not high enough. Therefore, under high dilution condition, it was difficult to remove the phenylsulfenyl group by tributyltin hydride.

Surprisingly, under similar cyclization condition with a final concentration of 0.05 M, selenide **14** gave only reduction product **8** in 62% yield, but at very dilute condition (0.01 M), cyclization occurred. In addition, we also observed the formation of selenide **16** (equation 1). This material presumably derived from selenium atom transfer[11] from **14** to the cyclized radical. Due to the difficulty of purification, we did not fully characterize **16**.[12]



(1)

16

Using similar methods described above, dithioacetals **19**, **22** and **23**, and α-chlorosulfides **27** and **28** were prepared (Scheme 3). In particular, we synthesized **19** and **22** via anionic substitution reaction of the corresponding α-chlorosulfides with sodium phenylthiolate in DMF. The results of radical cyclization reactions of these sulfides were collected in Table 1. When the olefin was terminally disubstituted with methyl groups, more cyclization products were observed (entry 4). This was because stabilization of the cyclized radical would increase the rate of cyclization. With a good Michael acceptor as in entries 5 and 6, cyclization became exclusive. Note that in the later two cases, the reactions were performed with higher concentration and shorter addition time of the tin hydride.

The stereochemistry of the cyclized products was determined by comparison of their ^{1}H NMR spectra with sulfide **10**. As shown in Table 2, SC-H absorptions of all *cis*-isomers occurred at about δ 3.70 and those of the *trans*-isomers occurred at higher field around δ 3.10. It is well known that C(1)-substituted 5-hexenyl ra-dical generally gives cyclization product with 1,2-*cis* selectivity.[13] However, in the case of the cyclization of **13** (Table 1, entry 1), *trans*-isomer was the major product. Comparison of entries 1, 4 and 5 revealed an interesting trend. As the cyclization became more efficient, the *cis*-product increased. In the case of entry 5, *cis*-product became major. We can rationalize this phenomenon by examining the chair-transition states[14] **A** and

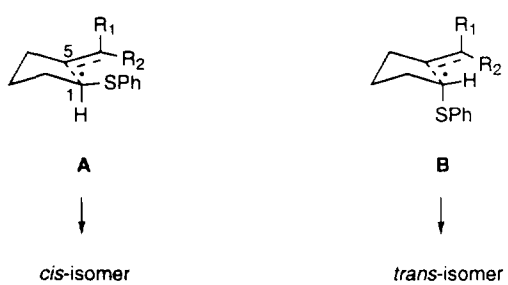
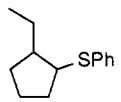
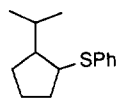
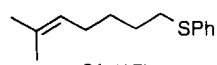
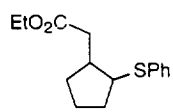


Table 1. Radical Cyclizations of **13**, **19**, **22**, **23**, **27** and **28**.

entry	starting material	cyclization product (% yield; *cis/trans* ratio)	reduction product (% yield)[a]	total yield (%)[b]
1[c]	**13**	**10** (52; 1/1.7)	**8** (32)	84
2[c]	**19**	 **29** (51; 1/1.9)	**18** (32)	83
3[c]	**22**[d]	**29** (48; 1/1.9)	**21** (26)	74
4[c,e]	**23**	 **30** (55; 1/1.2)	 **31** (17)	72
5[f,g,h]	**27**	 **32** (83; 1.9/1)	–	83
6[f,g,i]	**28**	**32** (67; 1.2/1)	–	67

[a]Based on ^{1}H NMR integration. [b]Isolation yield. [c]A 0.12 M benzene solution of tributyltin hydride and catalytic amount of AIBN was added over 6 h to a refluxing 0.1 M benzene solution of the dithioacetal. [d]A *cis* isomer enriched **22** was used (*cis/trans* = 85/15). [e]The tin hydride solution was added over 3.5 h. [f]The final concentration relative to the α-chlorosulfide was 0.1 M. [g]Triethylamine (0.2 equiv.) was added. [h]The tin hydride solution was added over 2.5 h. [i]The tin hydride solution was added over 45 min.

Table 2. Characteristic ^{1}H NMR Absorptions (δ; $CDCl_3$) of Cyclization Products .

entry	sulfide	SC-H of *cis*-isomer	SC-H of *trans*-isomer
1	**10**	3.62	3.02
2	**29**	3.69	3.12
3	**30**	3.72	3.28
4	**32**	3.76	3.10

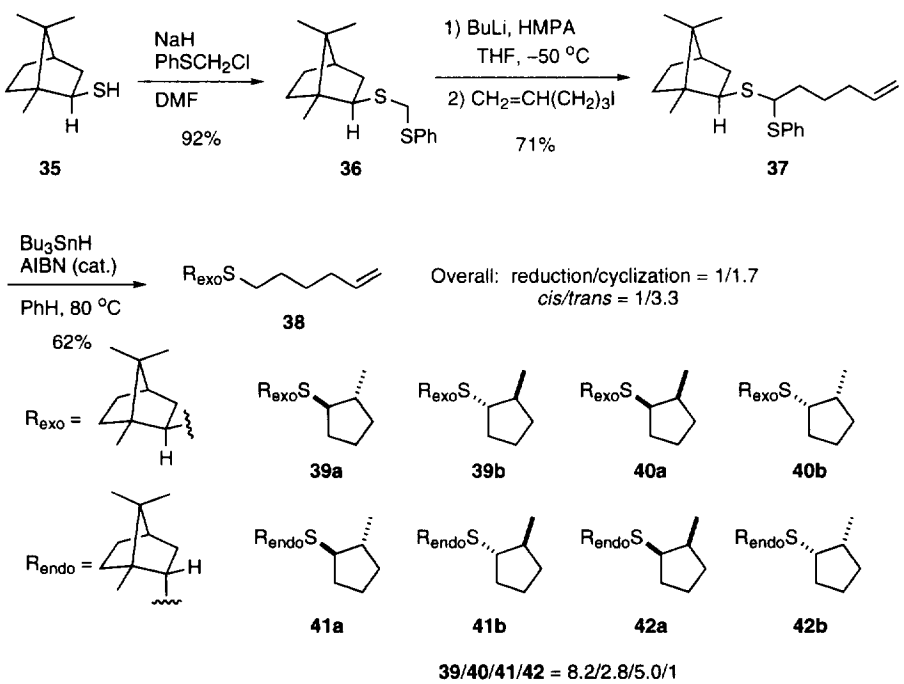
B. Although early transition state is usually proposed for radical cyclizations, a faster cyclization reaction will have a *relatively* earlier transition state. A slower reaction will have a *relatively* later transition state, and the extent of bond formation between C(1) and C(5) will be higher. Therefore, in the transition state of a slower cyclization reaction the phenylsulfenyl group is closer to the olefin, and the unfavorable steric repulsion increases the energy of **A**. Thus, a slower reaction gives higher proportion of *trans*-product, and a faster reaction gives higher proportion of *cis*-product. In the case of **28** (Table 1, entry 6), the *cis*-substituent of the olefin should adopt a pseudo-axial position (R_1 in **A** and **B**). The transition state energy will be higher, therefore the rate of cyclization will be slower than that of **27** (entry 5). Lower *cis/trans* ratio was indeed observed in entry 6.

33 **34**

R* = chiral auxiliary

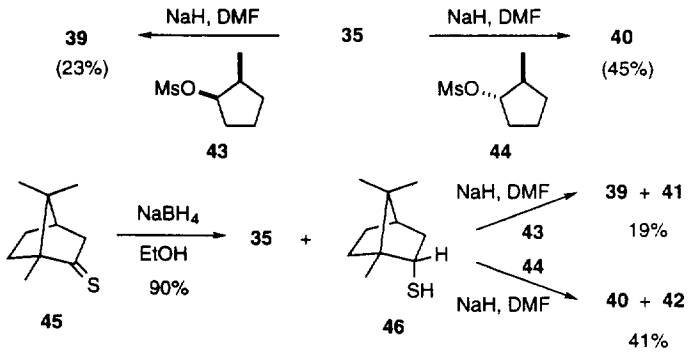
With the formation of asymmetric radical[15] in mind, we next turned our attention to develop a general methodology to generate radical such as **33**. We decided to prepare dithioacetal **34** for this purpose. As shown in Scheme 4, *dl*-isobornyl mercaptan (**35**)[16] was deprotonated with sodium hydride and then alkylated with chloromethyl phenyl sulfide to afford **36** in 92% yield. Alkylation of this dithioacetal with 5-iodopentene[10] using the condition described above gave **37** in 71% yield. This material was a mixture of isomers epimeric at

Scheme 4



35 **36** **37** **38** **39a** **39b** **40a** **40b** **41a** **41b** **42a** **42b**

Scheme 5



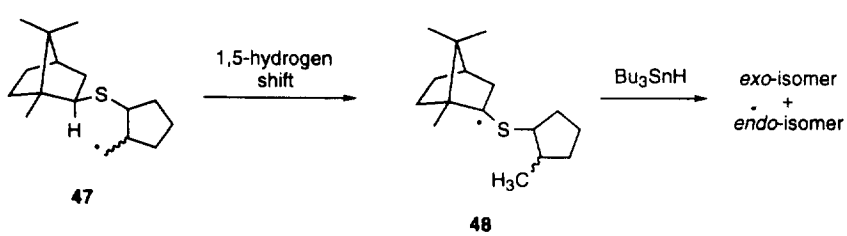
the dithioacetal carbon, and the ratio could not be determined. Since both isomers would generate the same radical, this mixture was used in our cyclization study.

Cyclization of **37** was carried out using our standard condition. The ratio of reduction/cyclization was determined as 1/1.7 via ^{1}H NMR integration, and the total yield was 62%. Since **38** was the only reduction product and sulfide **8** was not observed, the phenylsulfenyl group was selectively removed by tributyltin radical.[17] Analysis by HPLC showed the ratio of **39/40/41/42** as 8.2/2.8/5.0/1.0. Each of the four isomers existed as a pair of inseparable diastereomers in equal amount as judged by their ^{1}H NMR spectra. Therefore, the isobornyl group did not induce any diastereoselectivity for this cyclization.

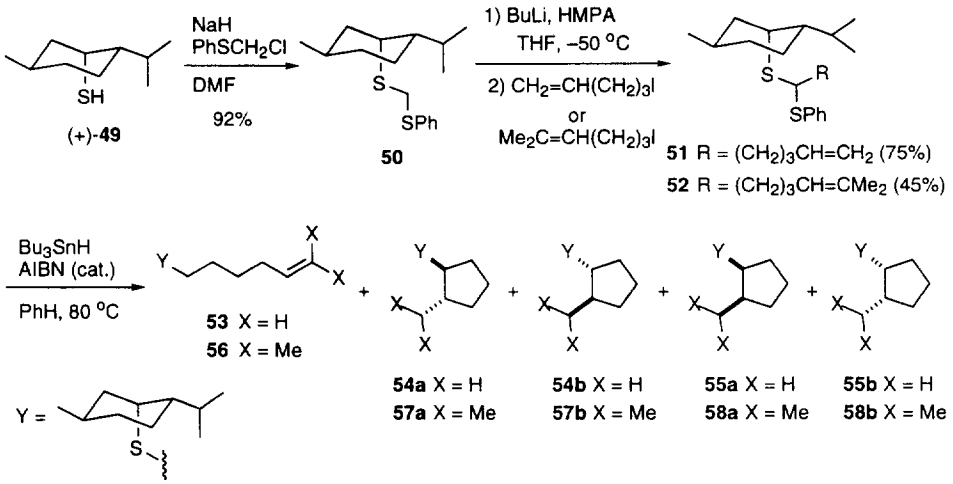
The structures of these cyclization products were identified by alternative synthesis (Scheme 5). Thus, coupling of thiol **35** with mesylates **43** and **44** afforded **39** and **40**, respectively. Because we could not prepare pure thiol **46**, a mixture of **35** and **46** (**35/46** = 7/3) obtained from sodium borohydride reduction of thione **45**[18] was used. Coupling of this mixture with **43** or **44** gave respectively a mixture of **39** and **41**, and a mixture of **40** and **42**.

The formation of bornyl sulfides **41** and **42** from the cyclization can be explained as shown in Scheme 6. After the initial cyclization, the resulting radical **47** underwent a 1,5-hydrogen transfer[19] to give radical **48**. Hydrogen abstraction of **48** from tributyltin hydride could proceed from *exo*- or *endo*-face. Therefore, epimerization at the C(2) position of the bornyl skeleton occurred. Since the hydrogen transfer process occurred after the cyclization, the overall *cis/trans* ratio (1/3.3) should reflect the original selectivity.

Scheme 6



Scheme 7



As shown in Scheme 7, we also prepared dithioacetal **50** (92%) from (+)-neomenthanethiol (**49**).[20] Deprotonation of **50** with butyllithium at –50 °C followed by alkylation with 5-iodopentene[10] or 6-iodo-2-methyl-2-hexene[21] gave **51** and **52** in 75% and 45% yield, respectively. Analysis by ^{1}H NMR showed that these two compounds existed as a 1 : 4 mixture of two epimers isomeric at the dithioacetal carbon. The mixtures were used in the cyclization studies. Cyclization of **51** with tributyltin hydride gave in 99% yield a mixture of reduction product **53**, and cyclization products **54** and **55**. The ratio of **53**/(**54** + **55**) was determined as 1/2.8 by ^{1}H NMR integration. The ratio of **54**/**55** was 3.3/1, and these two sulfides could be separated by HPLC. By ^{1}H NMR analysis, each sulfide existed as a pair of diastereomers in equal amount. Therefore, there was no facial selectivity of the olefin during cyclization. Similarly, **52** cyclized to give a mixture of **56**, **57** and **58** in 97% yield. The ratio of **56**/(**57** + **58**) was 1/9, and the ratio of **57**/**58** was 1.2/1. Again, a 1/1 ratio of **57a**/**57b** and **58a**/**58b** was observed.

Table 3. ^{1}H NMR Absorptions of C(1)-H on the Cyclopentane Ring of Cyclized Alkyl Sulfides.

entry	sulfide	chemical shift (δ)
1	**39a, 39b**	2.65
2	**54a, 54b**	2.45
3	**57a, 57b**	2.74
4	**40a, 40b**	3.01
5	**55a, 55b**	3.15
6	**58a, 58b**	3.15, 3.20

The stereochemistry of the cyclization products was determined based on the spectroscopic information obtained from the isobornyl system (Table 3, entries 1, 4). As shown in Table 3, the C(1)-H signal of the cyclopentane ring could be divided into two categories. For all the *trans* products (entries 1–3), the signal appeared at higher field centered around δ 2.60. The absorptions of the *cis* products (entries 4–6) appeared at lower field centered around δ 3.10.

In contrast to the isobornyl system, the neomenthyl system did not have the 1,5-hydrogen transfer problem as shown in Scheme 6. For **37** and **51**, the cyclizations all gave a *cis/trans* product ratio of 1/3.3. More *trans* cyclization product was observed than in the case of **13** (Table 1, entry 1). This probably reflects the inherent difference between an α-phenylsulfenyl and α-alkylsulfenyl radical.

In summary, diphenyl dithioacetals or phenyl α-chlorosulfides have been used to generate α-phenylsulfenyl radicals. The efficiency of intramolecular cyclizations of this type of radicals depends on the substitution pattern of the olefin. When the olefin is substituted with an ester group, cyclization is the predominant process. The *cis/trans* ratios of the cyclization products also vary according to the olefin substitution. For a faster cyclization reaction, the *cis* proportion increases. Dithioacetal with a phenylsulfenyl group and alkylsulfenyl group reacts selectively with tributyltin hydride to remove the phenylsulfenyl group. Although two chiral auxiliaries have been tested without detecting any chiral induction, a general methodology is established and can be used for future studies.

EXPERIMENTAL SECTION

^1H and ^{13}C NMR spectra were recorded on Varian EM-390 (operating at 90 MHz), Bruker AM-300WB (operating at 300 and 75 MHz) or Bruker AC-200 (operating at 200 and 50 MHz) spectrometers with tetramethylsilane (TMS) or $CHCl_3$ as internal standards and $CDCl_3$ as the solvent. Infrared spectra were taken on a Perkin-Elmer 938G instrument. Mass spectra were recorded on a Finigan TSQ-46C spectrometer. Exact masses were recorded on JEOL JMS-HX 110 or SX-102A spectrometers. Combustion analyses were done on a Perkin-Elmer 240C instrument. High-pressure liquid chromatography (HPLC) was carried out on a Hitachi L-6200 chromatograph equipped with a refractive index detector. The samples were analyzed and/or separated on a Hibar Lichrosorb Si 60 (7 μm) column (25 cm x 1 cm) with the indicated eluent with a 5 mL/min flow rate. Gas chromatography was performed on a Shimadzu GC-8A chromatograph. The samples were analyzed on a 3 M x 3.3 mm column packed with 10% SE-30 on Chromosorb W (80-100 mesh). Optical rotations were recorded on a Jasco DIP-360 spectrometer. Melting points were measured with a Mel-Temp apparatus and are uncorrected. Benzene and THF were distilled from sodium benzophenone ketyl under N_2. All reactions were performed under a blanket of N_2 or Ar.

6-Chloro-6-phenylthio-1-hexene (9). To a solution of 192 mg (1.0 mmol) of **8**[5] in 2 mL of carbon tetrachloride cooled in an ice-water bath was added 146 mg (1.1 mmol) of NCS. The resulting mixture was stirred at 0 °C for 2 h and then at room temperature for 12 h. The resulting mixture was filtered, and the filter cake was washed with 10 mL of hexane. The filtrate was concentrated in vacuo to give 222 mg (98%) of **9** as a pale yellow oil: IR (neat) 3075, 2930, 2860, 1638, 1582, 1474, 1437, 1025, 992, 914, 750, 690 cm^{-1}; ^1H NMR (300 MHz) δ 1.68 (quintet, J = 7 Hz, 2 H, CH_2), 2.00–2.14 (m, 4 H), 4.85–5.10 (m, 2 H, $=CH_2$),

5.25 (t, J = 7 Hz, 1 H, SCH), 5.77 (ddt, J = 15, 12, 7 Hz, 1 H, =CH–), 7.30–7.38 (m, 3 H, ArH), 7.50–7.54 (m, 2 H, ArH). This material was used directly in the next step without further purification.

Bis(phenylthio)methane (15).[9] To a mixture of 6 mL (43 mmol) of triethylamine and 4.4 mL (43 mmol) of thiophenol was added 50 mL of dichloromethane in one portion. The resulting solution was stirred at room temperature for 46 h and then partitioned between 300 mL of ether and 100 mL of sodium hydroxide solution (1 N). The organic layer was washed with 200 mL of brine, dried ($MgSO_4$), and concentrated in vacuo to give 5.47 g of a pale yellow liquid. The liquid was chromatographed over silica gel (eluted with hexane and then hexane/ethyl acetate, 1/9) to give 4.61 g (92%) of **15** as a white solid: mp 32–33 °C (lit[9] 36.0-37.5 °C).

6,6-Bis(phenylthio)-1-hexene (13). *Method A*: To a solution of 275 mg (1.2 mmol) of **9** in 2 mL of carbon tetrachloride was added 330 mg (2.4 mmol) of zinc chloride and 0.13 mL (1.2 mmol) of thiophenol. The resulting mixture was stirred at room temperature for 16 h and filtered. The filter cake was washed with 30 mL of hexane, and the filtrate was washed with 40 mL of sodium hydroxide solution (1 N). The organic phase was dried ($MgSO_4$), concentrated in vacuo, and the residual oil was chromatographed over silica gel (eluted with hexane) to give 253 mg (70%) of **13** as a colorless liquid.

Method B: To a solution of **15** (270 mg, 1.16 mmol) in 2 mL of THF cooled at –50 °C was added dropwise a solution of butyllithium in hexane (1.55 M; 0.85 mL, 1.32 mmol). After stirring at the same temperature for 5 min, 0.14 mL (16 mmol) of HMPA was added and the resulting solution was stirred for another 5 min. A solution of 5-iodopentene[10] (0.18 mL, 1.44 mmol) in 1 mL of THF was added dropwise, and the resulting mixture was stirred for another 10 min and then warmed up slowly to room temperature. The reaction mixture was partitioned between 50 mL of hexane and 50 mL of water. The organic layer was dried ($MgSO_4$), concentrated in vacuo, and the residual oil was chromatographed over silica gel (eluted with hexane) to give 310 mg (89%) of **13** as a colorless liquid: IR (neat) 3073, 2935, 1638, 1581, 1478, 1436, 1087, 1067, 1024, 991, 913, 748, 690 cm^{-1}; ^1H NMR (300 MHz) δ 1.70 (quintet, J = 7 Hz, 2 H, =C–C–CH_2), 1.86 (q, J = 7 Hz, 2 H, S–C–CH_2), 2.03 (q, J = 7 Hz, 2 H, allyl), 4.40 (t, J = 7 Hz, 1 H, SCH), 4.93 (dt, J = 9, 1.5 Hz, 1 H, =CH_2), 4.97 (dt, J = 15.5, 1.5 Hz, 1 H, =CH_2), 5.75 (ddt, J = 15.5, 9, 7 Hz, 1H, =CH–), 7.24–7.35 (m, 6 H, ArH), 7.41-7.47 (m, 4 H, ArH); ^{13}C NMR (50 MHz) δ 26.1, 33.0, 35.1, 58.2, 114.9, 127.6, 128.8, 132.6, 134.2, 138.0. Anal. Calcd for $C_{18}H_{20}S_2$: C, 71.95; H, 6.70. Found: C, 71.95; H, 6.63.

***cis*-1-Methyl-2-(phenylthio)cyclopentane (10).** To a solution of 0.38 mL (1.3 mmol) of tributylphosphine (85%) in 3 mL of THF was added 269 mg (1.3 mmol) of *N*-phenylsulfenylsuccinimide.[22] The resulting mixture was stirred at room temperature for 5 min followed by the addition of 103 mg (1 mmol) of *trans*-2-methylcylopentanol and then stirred for another 16 h. The reaction mixture was partitioned between 50 mL of hexane and 40 mL of water. The organic layer was dried ($MgSO_4$), concentrated, and the residue was chromatographed over silica gel (eluted with hexane) to give 154 mg (80%) of *cis*-**10** as a colorless liquid: IR (neat) 3071, 2958, 2868, 1582, 1478, 1449, 1091, 1025, 737, 690 cm^{-1}; ^1H NMR (200 MHz) δ 1.03 (d, J = 7 Hz, 3 H, Me), 1.47–1.84 (m, 5 H), 2.00–2.05 (m, 1 H), 2.30 (heptet, J = 7 Hz, 1 H, MeCH), 3.62 (q, J = 7 Hz, 1 H, SCH), 7.05–7.42 (m, 5 H, ArH); ^{13}C NMR (50 MHz) δ 16.1, 22.2, 32.1, 32.5, 37.8, 52.0,

Hz, 2 H, allyl), 4.10 (q, J = 7 Hz, 2 H, OCH_2), 5.20 (t, J = 6 Hz, 1 H, SCH), 5.70 (br d, J = 11 Hz, 1 H, COCH=), 6.10 (dt, J = 11, 7 Hz, 1 H, CO–C=CH), 7.15–7.70 (m, 5 H, ArH). This material was used directly without further purification.

Radical cyclization reaction of 27: ethyl 2-(2-(phenylthio)cyclopentyl)ethanoate (32). According to the general procedure, to a refluxing solution of **27** (586 mg, 1.96 mmol) and 0.055 mL (0.39 mmol) of triethylamine in 10 mL of benzene was added over 2.5 h a solution of tributyltin hydride (0.63 mL, 2.35 mmol) and AIBN (16 mg, 0.098 mmol) in 10 mL of benzene to give 429 mg (83%) of **32** as a pale yellow liquid. The *cis/trans* ratio was determined by ^{1}H NMR integration to be 1.9/1. **32**: ^{1}H NMR (300 MHz) δ 1.15–1.30 (two overlapped t, J = 7 Hz, at 1.19 (*cis*) and 1.22 (*trans*), 3 H, Me), 1.42–1.90 (m, 5 H), 1.95–2.68 (m, 4 H), 3.10 (q, J = 7 Hz, SCH of *trans*-isomer), 3.76 (q, J = 5.5 Hz, SCH of *cis*-isomer), 3.95–4.16 (two overlapped q, J = 7 Hz, at 4.04 and 4.10, OCH_2), 7.10–7.42 (m, 5 H, ArH). Anal. Calcd for $C_{15}H_{20}O_2S$: C, 68.15; H, 7.63. Found: C, 67.92; H, 7.86.

Radical cyclization reaction of 28. Similar to the cyclization of **27**, the reaction of 112 mg of **28** (0.37 mmol) with 0.119 mL (0.44 mmol) of tributyltin hydride added over 45 min afforded 98 mg (67%) of **32**. The *cis/trans* ratio was determined by ^{1}H NMR integration to be 1.2/1.

***dl*-Isobornyl (phenylthio)methyl sulfide (36).** To a mixture of 163 mg (4 mmol) of sodium hydride (60%) in 0.5 mL of DMF was added dropwise a solution of 408 mg (2.4 mmol) of **35**[16] and 0.268 mL (2 mmol) of chloromethyl phenyl sulfide in 1.5 mL of DMF. The resulting mixture was stirred at room temperature for 1 h and poured into 30 mL of ether and 20 mL of water. The organic layer was washed with brine (20 mL), dried ($MgSO_4$), concentrated, and the residual oil was chromatographed over silica gel (eluted with hexane) to give 542 mg (92%) of **36** as a pale yellow oil: IR (neat) 3052, 2955, 2911, 2859, 1583, 1475, 1432, 1393, 1179, 1087, 1069, 1022, 861, 734, 697, 686 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.82 (s, 3 H, Me), 0.92 (s, 3 H, Me), 0.98 (s, 3 H, Me), 1.10–1.30 (m, 2 H), 1.60–1.76 (m, 3 H), 1.82–1.95 (m, 2 H), 2.96 (dd, J = 8, 6 Hz, 1 H, C(2)-H), 4.01 (two AB doublets, J_{AB} = 16 Hz, at 3.99 and 4.03, 2 H, SCH_2), 7.22–7.37 (m, 3 H, ArH), 7.37–7.44 (m, 2 H, ArH); ^{13}C NMR (50 MHz) δ 14.0, 20.1, 20.4, 27.3, 38.3, 40.1, 40.6, 45.9, 47.4, 49.5, 53.8, 126.7, 128.9, 130.4, 135.8. Anal. Calcd for $C_{17}H_{24}S_2$: C, 69.81; H, 8.27. Found: C, 69.80; H, 8.13.

***dl*-Isobornyl 1-(phenylthio)-5-hexenyl sulfide (37).** According to Method B for the preparation of **13**, the reaction of 232 mg (0.8 mmol) of **36** with 0.135 mL (1.03 mmol) of 5-iodopentene gave 202 mg (71%) of **37** as a pale yellow liquid. This material is a mixture of two diastereomers: IR (neat) 3068, 2945, 2873, 1635, 1579, 1474, 1448, 1433, 1384, 1366, 1327, 1078, 1023, 989, 929, 747, 680 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.81–0.97 (four s at 0.81, 0.89, 0.95 and 0.97, 9 H, Me),1.10–1.32 (m, 2 H), 1.53–2.10 (m, overlapped with q, J = 7 Hz, at 2.02, 11 H, allyl and others), 2.98–3.09 (two overlapped dd, J = 8,6 Hz, at 3.01 and 3.05, 1 H, SCH), 3.99–4.10 (m, 1 H, SCHS), 4.94 (dd, J = 10, 1 Hz, 1 H, $=CH_2$), 4.96 (dd, J = 17, 1 Hz, 1 H, $=CH_2$), 5.76 (ddt, J = 17, 10, 1 Hz, 1 H, =CH–), 7.25–7.36 (m, 3 H, ArH), 7.37–7.49 (m, 2 H, ArH). Anal. Calcd for $C_{22}H_{32}S_2$: C, 73.27; H, 8.95. Found: C, 72.99; H, 9.08.

Radical cyclization reaction of 37. The reaction of **37** (150 mg, 0.42 mmol) and tributyltin hydride (0.17 mL, 0.63 mmol) according to the general procedure gave 66 mg (62%) of a mixture of **38–42**. The ratio of **38**/cyclization product was determined by ^{1}H NMR integration to be 1/1.7. Analysis by HPLC (eluted with hexane) showed the ratio of **39** (R_t = 10.7 min) : **40** (R_t = 9.9 min) : **41** (R_t = 13.7 min) : **42** (R_t = 12.4 min) as 8.2/2.8/5.0/1. **38**: R_t = 17.1 min; ^{1}H NMR (200 MHz) δ 0.82 (s, 3 H, Me), 0.97 (s, 3 H, Me), 1.00 (s, 3 H, Me), 1.15 (br d, *J* = 9 Hz, 2 H), 1.40–1.95 (m, 9 H), 2.07 (q, *J* = 7 Hz, 2 H, allyl), 2.52 (t, *J* = 8 Hz, 2 H, SCH_2), 2.63 (t, *J* = 7 Hz, 1 H, isobornyl SCH), 4.95 (dd, *J* = 10, 2 Hz, 1 H, $=CH_2$), 5.02 (dd, *J* = 17, 2 Hz, 1 H, $=CH_2$), 5.80 (ddt, *J* = 17, 10, 7 Hz, 1 H, =CH–). **39**: ^{1}H NMR (200 MHz) δ 0.82 (s, 3 H, Me), 0.90–1.28 (m, 18 H), 1.50–2.00 (m, 10 H), 2.00–2.06 (m, 1 H), 2.40–2.55 (m, 1 H, isobornyl SCH), 2.65 (q, *J* = 7 H, 1 H, cyclopentyl SCH). **40**: ^{1}H NMR (200 MHz) δ 0.82 (s, 3 H, Me), 0.92–1.00 (four line m, 9 H), 1.44 (br d, *J* = 10 Hz, 2 H), 1.50–2.04 (m, 9 H), 2.18 (heptet, *J* = 7 Hz, 1 H, CHMe), 2.58–2.69 (two overlapped t, *J* = 7 Hz, at 2.62 and 2.64, 1 H, isobornyl SCH), 3.01 (q, *J* = 7 H, 1 H, cyclopentyl SCH). Characteristic chemical shift of **41**: ^{1}H NMR (200 MHz) δ 2.91 (br d, *J* = 9 Hz, 1 H). Characteristic chemical shift of **42**: ^{1}H NMR (200 MHz) δ 2.88 (br d, *J* = 9 Hz, 1 H).

(+)-Neomenthyl (phenylthio)methyl sulfide (50). Similar to the preparation of **36**, the reaction of 277 mg (1.6 mmol) of (+)-**49**[20] with 0.18 mL (1.3 mmol) of chloromethyl phenyl sulfide afforded 364 mg (92%) of **50** as a white solid: mp 42.5–43 °C; $[\alpha]^{20}_D$ = +210° (c 1.9, $CHCl_3$); IR (neat) 3045, 2955, 2935, 2911, 2859, 1583, 1475, 1432, 1393, 1179, 1087, 1069, 1022, 861, 734, 697, 686 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.85–0.94 (four s at 0.85, 0.89, 0.92 and 0.94, 9 H, Me), 1.04–1.28 (m, 4 H), 1.50–2.02 (m, 5 H), 3.46 (br s, 1 H, SCH), 4.02 (two AB doublets, J_{AB} = 13 Hz, at 4.00 and 4.04, 2 H, SCH_2), 7.17–7.35 (m, 3 H, ArH), 7.35–7.44 (m, 2 H); ^{13}C NMR (50 MHz) δ 20.7, 21.0, 22.1, 26.3, 26.6, 29.6, 35.3, 37.3, 40.2, 46.5, 48.7, 126.6, 128.8, 130.0, 136.0. Anal. Calcd for $C_{17}H_{26}S_2$: C, 69.33; H, 8.90. Found: C, 69.23; H, 8.90.

Neomenthyl 1-(phenylthio)-5-hexenyl sulfide (51). According to Method B for the preparation of **13**, the reaction of 284 mg (0.97 mmol) of **50** with 0.15 mL (1.16 mmol) of 5-iodopentene gave 263 mg (75%) of **51** as a pale yellow liquid. This material is a 4/1 mixture of two diastereomers: IR (neat) 3068, 2939, 2912, 2863, 1635, 1579, 1473, 1434, 1380, 1364, 1279, 1167, 1086, 1065, 1024, 989, 911, 860, 747, 690 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.85 (d, *J* = 7 Hz, 6 H, Me), 1.01 (d, *J* = 7 Hz, 3 H, Me), 1.05–1.30 (m, 4 H), 1.45–2.14 (m, 11 H), 3.40 (br s, 0.2 H, SCH), 3.49 (br s, 0.8 H, SCH), 4.07 (dd, *J* = 8,5 Hz, 1 H, SCHS), 4.91 (dd, *J* = 11. 2 Hz, 1 H, $=CH_2$), 4.95 (dd, *J* = 17, 2 Hz, 1 H, $=CH_2$), 5.74 (ddt, *J* = 17, 11, 2 Hz, 1 H, =CH–), 7.23–7.47 (m, 3 H, ArH), 7.47–7.48 (m, 2 H, ArH). Anal. Calcd for $C_{22}H_{34}S_2$: C, 72.87; H, 9.45. Found: C, 72.63; H, 9.72.

Radical cyclization reaction of 51. The reaction of **51** (144 mg, 0.40 mmol) and tributyltin hydride (0.16 mL, 0.59 mmol) according to the general procedure gave 99 mg (99%) of a mixture of **53–55**. The ratio of **53**/(**54** + **55**) was determined to be 1/2.8 by ^{1}H NMR integration, and the ratio of **54**/**55** was 3.3/1. **53**: ^{1}H NMR (200 MHz) δ 0.72–1.02 (m, 9 H), 1.02–1.30 (m, 5 H), 1.58–1.80 (m, 6 H), 1.80–1.24 (m, 2 H), 2.17 (q, *J* = 7 Hz, 2 H, allyl), 2.50 (t, *J* = 7 Hz, 2 H, SCH_2), 3.09 (br s, 1 H, SCH), 4.96 (dd, *J* = 9, 2 Hz, 1 H, $=CH_2$), 5.03 (dd, *J* = 16, 2 Hz, 1 H, $=CH_2$), 5.79 (ddt, *J* = 16, 9, 2 Hz, 1 H, =CH–). **54**: ^{1}H NMR (200

125.6, 128.7, 129.7, 137.3; MS *m/z* (rel intensity) 192 (M^+, 55), 149 (2), 135 (10), 110 (100), 83 (30), 67 (20), 55 (50); HRMS calcd for $C_{12}H_{16}S$ *m/z* 192.0973, found 192.0968.

***trans*-1-Methyl-2-(phenylthio)cyclopentane (10).** According to the procedure for the preparation of *cis*-**10**, the reaction of 49 mg (0.49 mmol) of *cis*-2-methylcylopentanol,[23] 183 μL (0.64 mmol) of tributylphosphine and 152 mg (0.74 mmol) of *N*-phenylsulfenylsuccinimide[22] gave 16 mg (17%) of *trans*-**10** as a pale yellow liquid: IR (neat) 3057, 2954, 2866, 1582, 1478, 1449, 1435, 1092, 1025, 737, 690 cm^{-1}; ^1H NMR (300 MHz) δ 1.07 (d, *J* = 6.5 Hz, 3 H, Me), 1.16–1.35 (m, 2 H), 1.50–1.75 (m, 2 H), 1.75–2.03 (m, 2 H), 2.05–2.25 (m, 1 H), 3.02 (q, *J* = 7 Hz, 1 H, SCH), 7.10–7.39 (m, 5 H, ArH).

General procedure for radical cyclization reactions. To a refluxing solution of 1 mmol of the dithioacetal in 10 mL of deoxygenated benzene was added over 6 h a solution of 1.5 mmol of tributyltin hydride and 0.05 mmol of AIBN in 10 mL of deoxygenated benzene. The resulting solution was heated for another 8 h and then directly concentrated in vacuo. To the residue was added a few drops of wet triethylamine[24] and then chromatographed over silica gel using hexane/ethyl acetate as eluent to separate the products.

Radical cyclization reaction of 13. The reaction of **13** (245 mg, 0.82 mmol) and tributyltin hydride (0.33 mL, 1.23 mmol) according to the general procedure gave 132 mg (84%) of a mixture of **8**, *cis*- and *trans*-**10**. The ratio of *cis*-**10**/*trans*-**10**/**8** determined by ^1H NMR integration was 1/1.7/1.7. Gas chromatography analysis (column temperature = 160 °C, flow rate = 32 mL/min) of this mixture showed R_t of *trans*-**10** at 14.2 min, **8** at 15.2 min and *cis*-**10** at 16.9 min. Characteristic ^1H NMR (200 MHz) absorptions of **8**:[5] δ 2.92 (t, *J* = 7 Hz, 2 H, SCH_2), 4.87–5.05 (m, 2 H, $=CH_2$), 5.78 (ddt, *J* = 18, 10, 7 Hz, 1 H, =CH–).

***trans*-7-Phenylthio-2-heptene (18).** To a solution of 345 mg (3.03 mmol) of *trans*-5-hepten-1-ol[25] and 0.632 mL (4.54 mmol) of triethylamine in 3 mL of dichloromethane cooled at 0 °C was added dropwise over 10 min a solution of 0.283 mL (3.63 mmol) of methanesulfonyl chloride in 2.5 mL of dichloromethane. The resulting mixture was stirred at the same temperature for 2 h and then partitioned between 50 mL of dichloromethane and 30 mL of water. The organic layer was washed with 1 N sodium hydroxide solution (30 mL), dried (Na_2SO_4) and concentrated in vacuo to give 543 mg of the crude mesylate. To 6 mL of absolute ethanol was added 68 mg (2.97 mmol) of sodium, and the resulting mixture was stirred until the sodium disappeared. Thiophenol (0.305 mL, 2.97 mmol) was added and then stirred for another 15 min. To the resulting solution was added over 10 min a solution of the mesylate prepared above in 3 mL of absolute ethanol. The reaction mixture was stirred for 17 h and then partitioned between 50 mL of ether and 30 mL of 1 N sodium hydroxide solution. The organic layer was washed with brine (30 mL), dried ($MgSO_4$), concentrated, and the residue was chromatographed over silica gel (eluted with hexane) to give 518 mg (85%) of **18** as a colorless liquid: IR (neat) 3017, 2928, 2851, 1582, 1478, 1435,1092, 1025, 966, 737, 689 cm^{-1}; ^1H NMR (90 MHz, CCl_4) δ 1.30–1.70 (m, 7 H), 1.70–2.10 (m, 2 H, $=C-CH_2$), 2.80 (t, *J* = 7 Hz, 2 H, SCH_2), 5.20–5.40 (m, 2 H, vinyl), 6.60–7.40 (m, 5 H, ArH); MS *m/z* (rel intensity) 207 (28), 206 (M^+, 100), 192 (24), 137 (19), 123 (33), 111 (22), 97 (43), 82 (38), 68 (41), 67 (57), 54 (34); HRMS calcd for $C_{13}H_{18}S$ *m/z* 206.1129, found 206.1122.

***trans*-7,7-Bis(phenylthio)-2-heptene (19).** To a solution of 118 mg (0.57 mmol) of **18** in 1 mL of carbon tetrachloride was added 92 mg (0.69 mmol) of NCS. The resulting mixture was stirred at room temperature for 17 h, filtered and concentrated in vacuo to give 141 mg of the crude chloride. To 47 mg (1.2 mmol) of sodium hydride (60%) under DMF (0.6 mL) was added 0.090 mL (0.88 mmol) of thiophenol in one portion. The resulting mixture was stirred for 30 min followed by the addition of a solution of the chloride prepared above in 0.6 mL of DMF and then stirred at room temperature for 44 h. The reaction mixture was partitioned between 30 mL of ether and 20 mL of 1 N sodium hydroxide solution. The organic layer was washed with brine (20 mL), dried ($MgSO_4$), and concentrated in vacuo. The residual oil was chromatographed over silica gel (eluted with hexane) to give 105 mg (57%) of **19** as a colorless liquid: IR (neat) 3070, 3016, 2932, 2852, 1580, 1477, 1435, 1087, 1066, 1024, 966, 747, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.48–2.20 (m, 9 H), 4.27 (t, J = 6 Hz, 1 H, SCH), 5.17–5.43 (m, 2 H, vinyl), 7.05–7.55 (m, 10 H, ArH); MS *m/z* (rel intensity) 314 (M^+, 29), 207 (38), 206 (100), 191 (78), 149 (78), 137 (82), 124 (30), 111 (34), 109 (34), 103 (29), 67 (71), 55 (57); HRMS calcd for $C_{19}H_{22}S_2$ *m/z* 314.1163, found 314.1185.

Radical cyclization reaction of 19. The reaction of **19** (105 mg, 0.34 mmol) and tributyltin hydride (0.14 mL, 0.50 mmol) according to the general procedure gave 57 mg (83%) of a mixture of **18** and **29**. The ratio of **18**/*cis*-**29**/*trans*-**29** was determined by ^{1}H NMR integration to be 1.9/1/1.9. Characteristic ^{1}H NMR (300 MHz) absorptions of **29**: δ 0.80–1.00 (two overlapped t, J = 7 Hz, at 0.91 and 0.93, 3 H, Me), 3.12 (q, J = 7 Hz, 1 H, SCH of *trans*-isomer), 3.69 (td, J = 6, 4 Hz, 1 H, SCH of *cis*-isomer).

***cis*-7-Phenylthio-2-heptene (21).** From 1.314 g (11.5 mmol) of *cis*-enriched 5-hepten-1-ol (*cis*/*trans* = 85/15) using the procedure for the preparation of **18**, we obtained 1.996 g (84%) of *cis*-enriched **21**: IR (neat) 3012, 2928, 2852, 1582, 1478, 1435,1091, 1025, 966, 737, 689 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.30–1.83 (m, 7 H), 1.83–2.20 (m, 2 H, =C–CH_2), 2.83 (t, J = 7 Hz, 2 H, SCH_2), 5.25–5.50 (m, 2 H, vinyl), 7.05–7.40 (m, 5 H, ArH); MS *m/z* (rel intensity) 207 (12), 206 (M^+, 79), 123 (53), 110 (100), 96 (65), 81 (53), 68 (21), 67 (20), 55 (55); HRMS calcd for $C_{13}H_{18}S$ *m/z* 206.1129, found 206.1122.

***cis*-7,7-Bis(phenylthio)-2-heptene (22).** From 234 mg (1.14 mmol) of **21** using the procedure for the preparation of **19**, we obtained 241 mg (67%) of *cis*-enriched **22**: IR (neat) 3070, 3055, 3015, 2933, 2852, 1580, 1477, 1435, 1087, 1066, 1024, 966, 747, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.30–2.15 (m, 9 H), 4.27 (t, J = 6 Hz, 1 H, SCH), 5.15–5.37 (m, 2 H, vinyl), 7.07–7.55 (m, 10 H, ArH); MS *m/z* (rel intensity) 314 (M^+, 6), 207 (46), 206 (100), 122 (53), 96 (27); HRMS calcd for $C_{19}H_{22}S_2$ *m/z* 314.1163, found 314.1185.

Radical cyclization reaction of 22. The reaction of **22** (103 mg, 0.33 mmol) and tributyltin hydride (0.13 mL, 0.49 mmol) according to the general procedure gave 50 mg (74%) of a mixture of **21** and **29**. The ratio of **21**/*cis*-**29**/*trans*-**29** was determined by ^{1}H NMR integration to be 1.6/1/1.9.

2-Methyl-7,7-bis(phenylthio)-2-heptene (23). According to Method B for the preparation of **13**, the reaction of 523 mg (2.25 mmol) of **15** with 596 mg (2.48 mmol) of 6-iodo-2-methyl-2-hexene[21] gave 658 mg (89%) of **23** as a pale yellow liquid: IR (neat) 3055, 2963, 2925, 2854, 1580, 1477, 1435, 1087, 1067, 1024,

738, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.45–2.13 (m overlapped with two s at 1.50 and 1.60, 12 H), 4.21 (t, J = 6 Hz, 1 H, SCH), 4.97 (br t, J = 7 Hz, 1 H, vinyl), 7.07–7.50 (m, 10 H, ArH). Anal. Calcd for $C_{20}H_{24}S_2$: C, 73.12; H, 7.36. Found: C, 72.89; H, 7.53.

Radical cyclization reaction of 23. The reaction of **23** (112 mg, 0.34 mmol) and tributyltin hydride (0.14 mL, 0.50 mmol) according to the general procedure with tin hydride added over 3.5 h gave 54 mg (72%) of a mixture of **30** and **31**. The ratio of *cis*-**30**/*trans*-**30**/**31** was determined by ^{1}H NMR integration to be 1.5/1.8/1. Characteristic ^{1}H NMR (300 MHz) absorptions of *cis*-**30**: δ 0.92 (d, J = 7 Hz, 3 H, Me), 1.03 (d, J = 7 Hz, 3 H, Me), 3.72 (br s, 1 H, SCH). *trans*-**30**: δ 0.66 (d, J = 7 Hz, 3 H, Me), 0.96 (d, J = 7 Hz, 3 H, Me), 3.28 (td, J = 7, 4 Hz, SCH). **31**: IR (neat) 3055, 2925, 2853, 1582, 1478, 1435, 1374, 1090, 1025 737, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.30–1.70 (m overlapped with two s at 1.58 and 1.64, 10 H), 1.95 (br q, J = 7 Hz, 2 H, allyl), 2.86 (t, J = 7 Hz, 2 H, SCH_2), 5.02 (br t, J = 7 Hz, 1 H, vinyl), 7.10–7.30 (m, 5 H, ArH). Anal. Calcd for $C_{14}H_{20}S$: C, 76.30; H, 9.15. Found: C, 75.62; H, 9.23.

Ethyl *trans*-7-phenylthio-2-heptenoate (25) and ethyl *cis*-7-phenylthio-2-heptenoate (26). From 1.26 g (7.30 mmol) of a *cis/trans* mixture of ethyl 7-hydroxy-2-heptenoate[26] using the procedure for the preparation of **18**, we obtained 172 mg (9%) of **26** and 1.44 g (76%) of **25** as pale yellow liquids. **25**: IR (neat) 3057, 2933, 1717, 1649, 1479, 1436, 1366, 1304, 1266, 1183, 1137, 1092, 1042, 1025, 979, 739, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.23 (t, J = 7 Hz, 3 H, Me), 1.43–1.77 (m, 4 H), 2.00–2.33 (m, 2 H, allyl), 2.80 (br t, J = 6 Hz, 2 H, SCH_2), 4.03 (q, J = 7 Hz, 2 H, OCH_2), 5.61 (br d, J = 15 Hz, 1 H, COCH=), 6.71 (dt, J = 15, 7 Hz, 1 H, CO–C=CH), 6.93–7.30 (m, 5 H, ArH). Anal. Calcd for $C_{15}H_{20}O_2S$: C, 68.15; H, 7.63. Found: C, 68.18, H, 7.82. **26**: IR (neat) 3057, 2980, 2929, 2857, 1713, 1639, 1582, 1478, 1436, 1413, , 1233, 1186, 1093, 1033, 822, 739, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.23 (t, J = 7 Hz, 3 H, Me), 1.43–1.77 (m, 4 H), 2.61 (br q, J = 7 Hz, 2 H, allyl), 2.81 (br t, J = 6 Hz, 2 H, SCH_2), 4.05 (q, J = 7 Hz, 2 H, OCH_2), 5.60 (br d, J = 12 Hz, 1 H, COCH=), 6.03 (dt, J = 12, 7 Hz, 1 H, CO–C=CH), 6.95–7.50 (m, 5 H, ArH). Anal. Calcd for $C_{15}H_{20}O_2S$: C, 68.15; H, 7.63. Found: C, 67.67; H, 7.85.

Ethyl *trans*-7-chloro-7-phenylthio-2-heptenoate (27). A mixture of 500 mg (1.89 mmol) of **25** and 268 mg (2.01 mmol) of NCS in 4 mL of carbon tetrachloride was stirred at room temperature for 14 h and then filtered. The filter cake was rinsed with hexane, and the filtrate was concentrated to give 564 mg (100%) of **27** as a pale yellow liquid: IR (neat) 3057, 2980, 2937, 1711, 1650, 1474, 1438, 1366, 1306, 1270, 1188, 1093, 1042, 979, 750, 691 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.23 (t, J = 7 Hz, 3 H, Me), 1.47–2.40 (m, 6 H), 4.13 (q, J = 7 Hz, 2 H, OCH_2), 5.20 (t, J = 6 Hz, 1 H, SCH), 5.78 (br d, J = 15 Hz, 1 H, COCH=), 6.83 (dt, J = 15, 6 Hz, 1 H, CO–C=CH), 7.13–7.73 (m, 5 H, ArH). This material was used directly without further purification.

Ethyl *cis*-7-chloro-7-phenylthio-2-heptenoate (28). A mixture of 100 mg (0.38 mmol) of **26** and 54 mg (0.40 mmol) of NCS in 1 mL of carbon tetrachloride was stirred at room temperature for 15 h and then filtered. The filter cake was rinsed with hexane, and the filtrate was concentrated to give 112 mg (98%) of **27** as a pale yellow liquid: IR (neat) 3058, 2980, 2935, 1711, 1640, 1474, 1438, 1413, 1288, 1094, 1033, 822, 748, 690 cm $^{-1}$; ^{1}H NMR (90 MHz, CCl_4) δ 1.24 (t, J = 7 Hz, 3 H, Me), 1.47–2.25 (m, 4 H), 2.70 (br q, J = 7

MHz) δ 0.84–1.00 (m, 9 H), 1.00–1.35 (m overlapped with two d, J = 7 Hz, at 1.08 and 1.09, 7 H), 1.55–2.20 (m, 9 H), 2.45 (br q, J = 7 Hz, 1 H, cyclopentyl SCH), 3.10–3.24 (two overlapped br s at 3.16 and 3.20, 1 H, neomenthyl SCH). **55**: ^{1}H NMR (200 MHz) δ 0.72–1.33 (m, 16 H), 1.33–1.84 (m, 9 H), 2.90–3.08 (two overlapped q, J = 7 Hz, at 2.97 and 3.00, 1 H, cyclopentyl SCH), 3.15 (br s, 1 H, neomenthyl SCH).

Neomenthyl 1-(phenylthio)-6 methyl-5-heptenyl sulfide (52). According to the procedure for the preparation of **23**, the reaction of 215 mg (0.73 mmol) of **50** with 199 mg (0.89 mmol) of 6-iodo-2-methyl-2-hexene[21] gave 128 mg (45%) of **52** as a pale yellow liquid. This material is a 4/1 mixture of two diastereomers: IR (neat) 3056, 2920, 2867, 1579, 1452, 1377, 1368, 1281, 1194, 1063, 1024, 989, 911, 860 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.88 (d, J = 7 Hz, 6 H, Me), 1.01 (d, J = 7 Hz, 3 H, Me), 1.06–1.33 (m, 4 H), 1.40–2.10 (m overlapped with two br s at 1.55 and 1.64, 16 H, =C-Me and others), 3.39 (br s, 0.2 H, SCH), 3.59 (br s, 0.8 H, SCH), 4.02–4.13 (two overlapped dd, J = 8, 5 Hz, at 4.06 (0.2 H) and 4.10 (0.8 H), SCHS), 5.03 (br t, J = 7 Hz, 1 H, =CH–), 7.19–7.36 (m, 3 H, ArH), 7.40–7.47 (m, 2 H, ArH). Anal. Calcd for $C_{24}H_{38}S_2$: C, 73.78; H, 9.80. Found: C, 73.72; H, 10.30.

Radical cyclization reaction of 52. The reaction of **52** (116 mg, 0.30 mmol) and tributyltin hydride (0.12 mL, 0.45 mmol) according to the general procedure gave 81 mg (97%) of a mixture of **56–58**. The ratio of **56**/(**57** + **58**) was determined to be 1/9 by ^{1}H NMR integration, and the ratio of **57/58** was 1.2/1. **56**: ^{1}H NMR (200 MHz) δ 0.73–1.83 (m overlapped with two s at 1.60 and 1.68, 25 H), 1.84–2.06 (m, 4 H), 2.48 (t, J = 7 Hz, 2 H, SCH_2), 3.11 (br s, 1 H, SCH), 5.11 (br t, J = 7 Hz, 1 H, =CH–). All products were separable by HPLC (eluted with hexane). **57a** and **57b**: one isomer appeared at R_t = 8.0 min; ^{1}H NMR (200 MHz) δ 0.82–1.34 (m, 20 H), 1.49–1.88 (m, 9 H), 1.89–2.03 (m, 3 H), 2.74 (q, J = 7 Hz, 1 H, cyclopentyl SCH), 3.20 (br s, 1 H, neomenthyl SCH); another isomer appeared at R_t = 8.9 min; ^{1}H NMR (200 MHz) δ 0.84–1.32 (m, 20 H), 1.49–1.81 (m, 9 H), 1.83–2.03 (m, 3 H), 2.74 (q, J = 7 Hz, 1 H, cyclopentyl SCH), 3.13 (br s, 1 H, neomenthyl SCH). **58a** and **58b**: one isomer appeared at R_t = 5.8 min; ^{1}H NMR (200 MHz) δ 0.86–1.50 (m, 20 H), 1.50–2.20 (m, 12 H), 3.09 (br s, 1 H, neomenthyl SCH), 3.15 (br t, J = 4 Hz, 1 H, cyclopentyl SCH); another isomer appeared at R_t = 6.3 min; ^{1}H NMR (200 MHz) δ 0.84–1.94 (m, 32 H), 3.09 (br s, 1 H, neomenthyl SCH), 3.20 (br t, J = 4 Hz, 1 H, cyclopentyl SCH).

ACKNOWLEDGMENT

Financial support by the National Science Council of the Republic of China is gratefully acknowledged.

REFERENCES AND NOTES

1. (a) *Chemistry of Organosulfur Compounds: general problems*; Belen'kii, L. I., Ed.; Ellis Horwood: New York, 1990. (b) Oae, S. *Organic Sulfur Chemistry: Structure and Mechanism*; Doi, J. T., Associate Ed.; CRC press: London, 1991. (c) *The Chemistry of Sulfur-containing functional groups*; Patai, S.; Rappoport, Z., Eds.; John Wiley and Sons, Inc.: New York, 1993.

2. (a) For a preliminary account of this report see Tsai, Y.-M.; Chang, F.-C.; Huang, J.; Shiu, C.-L. *Tetrahedron Lett.* **1989**, *30*, 2121–2124. (b) Korth, H.-G.; Sustmann, R. *J. Org. Chem.* **1988**, *53*, 4364–4369. (c) De Mesmaeker, A.; Hoffmann, P.; Ernst, B. *Tetrahedron Lett.* **1988**, *29*, 6585–6588. (d) Sato, T.; Wada, Y.; Nishimoto, M.; Ishibashi, H.; Ikeda, M. *J. Chem. Soc. Perkin Trans. 1*, **1989**, 879–886. (e) Sato, T.; Chono, N.; Ishibashi, H.; Ikeda, M. *J. Chem. Soc. Perkin Trans. 1*, **1995**, 1115–1120, and references cited therein. (f) Kim, S.; Fuchs, P. L. *J. Am. Chem. Soc.* **1991**, *113*, 9864–9865. (g) Yadav, V.; Fallis, A. G. *Can. J. Chem.* **1991**, *69*, 779–789. (h) Saicic, R. N.; Cekovic, Z. *Tetrahedron Lett.* **1994**, *35*, 7845–7848. (i) Mander, L. N.; Sherburn, M. S. *Tetrahedron Lett.* **1996**, *37*, 4255–4258.

3. For α-sulfonyl radical see: (a) Ueno, Y.; Khare, R. K.; Okawara, M. *J. Chem. Soc. Perkin Trans. 1*, **1983**, 2637–2640. (b) Rentrkul, V.; Poolsanong, C.; Pohmakotr, M. *Tetrahedron Lett.* **1989**, *30*, 6913–6919, and references cited therein. (c) Clive, D. L. J.; Biovin, T. L. B. *J. Org. Chem.* **1989**, *54*, 1997–2003. (d) Renaud, P. *Tetrahedron Lett.* **1990**, *31*, 4601–4604. (e) Singleton, D. A.; Church, K. M. *J. Org. Chem.* **1990**, *55*, 4780–4782. (f) Singleton, D. A.; Church, K. M.; Lucero, M. J. *Tetrahedron Lett.* **1990**, *31*, 5551–5554. (g) Renaud, P.; Schubert, S. *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 433–434. (h) Renaud, P.; Vionnet, J.-P.; Vogel, P. *Tetrahedron Lett.* **1991**, *32*, 3491–3494. (i) Samat, A.; Vacher, B.; Chanon, M. *J. Org. Chem.* **1991**, *56*, 3524–3530. (j) Boivin, J.; Crépon, E.; Zard, S. Z. *Tetrahedron Lett.* **1991**, *32*, 199–202. (k) Tsai, Y.-M.; Ke, B.-W.; Yang, C.-T.; Lin, C.-H. *Tetrahedron Lett.* **1992**, *33*, 7895–7898. (l) Flynn, D. L.; Zabrowski, D. L.; Nosal, R. *Tetrahedron Lett.* **1992**, *33*, 7281–7282. (m) Flynn, D. L.; Becker, D. P.; Nosal, R.; Zabrowski, D. L. *Tetrahedron Lett.* **1992**, *33*, 7283–7286. (n) Mahadevan, A.; Fuchs, P. L. *J. Am. Chem. Soc.* **1995**, *117*, 3272–3273. (o) Adrio, J.; Carrretero, J. C.; Arrayás, R. G. *Synlett* **1996**, 640–642.

4. Dilworth, B. M.; McKervey, M. A. *Tetrahedron* **1986**, *42*, 3731–3752.

5. Russel, G. A.; Ngoviwatchai, P.; Tashtoush, H. I.; Pla-Dalmau, A.; Khanna, R. K. *J. Am. Chem. Soc.* **1988**, *110*, 3530–3538.

6. Walker, K. A. M. *Tetrahedron Lett.* **1977**, 4475–4478.

7. For the reduction of dithioacetal by tributyltin hydride see Gutierrez, C. G.; Stringham, R. A.; Nitasaka, T.; Glasscock, K. G. *J. Org. Chem.* **1980**, *45*, 3393–3395. For another way to cleave the C-S bond see Arya, P.; Wayner, D. D. M. *Tetrahedron Lett.* **1991**, *32*, 6265–6268.

8. Cronin, J. P.; Dilworth, B. M.; McKervey, M. A. *Tetrahedron Lett.* **1986**, *27*, 757–760.

9. Cohen, T.; Ritter, R. H.; Ouellette, D. *J. Am. Chem. Soc.* **1982**, *104*, 7142–7148.

10. Schultz, A. G.; Lavieri, F. P.; Snead, T. E. *J. Org. Chem.* **1985**, *50*, 3086-3091.

11. Renaud, P.; Abazi, S. *Synthesis* **1996**, 253–258, and references cited therein.

12. Characteristic ^{1}H NMR (300 MHz, $CDCl_3$) signals for *trans*-**16**, δ 2.64 (dd, J = 16, 12 Hz, 1 H, $SeCH_2$), 2.87 (td, J = 11, 7 Hz, 1 H, SCH), 3.06 (dd, J = 16, 4 Hz, 1 H, $SeCH_2$); *cis*-**16**, δ 2.22–2.38 (a seven line m, 1 H), 2.45–2.58 (m, 2 H), 2.74 (t, J = 9 Hz, 1 H, $SeCH_2$), 3.45 (q, J = 8.5 Hz, 1 H, SCH).

13. Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073–3100.

14. (a) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron Lett.* **1985**, *26*, 373–376. (b) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925–3941. (c) Spellmeyer, D. C.; Houk, K. N. *J. Org. Chem.* **1987**, *52*, 959–974.

15. Smadja, W. *Synlett* **1994**, 1–26.
16. Subluskey, L. A.; King, L. C. *J. Am. Chem. Soc.* **1951**, *73*, 2647–2650.
17. For selective desulfurization of unsymmetrical sulfides see Gutierrez, C. G.; Summerhays, L. R. *J. Org. Chem.* **1984**, *49*, 5206–5213.
18. Wilson, S. R.; Caldera, P.; Jester, M. A. *J. Org. Chem.* **1982**, *47*, 3319–3321.
19. Beckwith, A. L. J.; Ingold, K. U. *Rearrangement in the Ground and Ecited States*; de Mayo, P., Ed.; Academic: New York, 1980; Vol. 1, p 161.
20. Strijtveen, B.; Kellogg, R. M. *J. Org. Chem.* **1986**, *51*, 3664–3671.
21. Jackson, A. C.; Goldman, B. E.; Snider, B. B. *J. Org. Chem.* **1984**, *49*, 3988–3994.
22. Groebel, W. *Chem. Ber.* **1960**, *93*, 284–285.
23. Rei, M.-H. *J. Org. Chem.* **1978**, *43*, 2173–2178.
24. Curran, D. P.; Chang, C.-T. *J. Org. Chem.* **1989**, *54*, 3140–3157.
25. Knight, J. A.; Diamond, J. H. *J. Org. Chem.* **1959**, *24*, 400–403.
26. Coveney, D. J.; Patel, V. F.; Pattenden, G.; Thompson, D. M. *J. Chem. Soc. Perkin Trans. 1*, **1990**, 2721-2728.

(*Received in Japan* 20 *December* 1996; *accepted* 5 *February* 1997)