The Scope and Limitations of Intramolecular Radical Cyclizations of Acylsilanes with Alkyl, Aryl, and Vinyl Radicals

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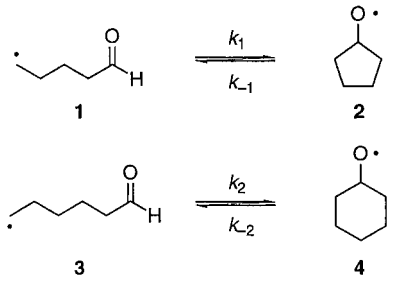
5-*Exo* cyclizations of primary and secondary radicals with acylsilanes successfully give cyclopentyl silyl ethers. The corresponding 6-*exo* cyclizations are sensitive to changes of the size of silyl groups. Secondary radicals undergo 6-*exo* cyclizations with acylsilanes more slowly. Reaction of aryl radical with acylsilane proceeds well for 5-*exo* cyclization but not for 6-*exo* cyclization. Vinyl radicals give best results in 5-*exo* cyclizations with acylsilanes but give low yields (∼30%) in 6-*exo* cyclizations. Intramolecular cyclizations of vinyl radicals with acylsilanes give enol silyl ethers regiospecifically.

Introduction

Radical addition to carbon−carbon multiple bonds is an important strategy in the construction of carbocycles or heterocycles.[1] A carbon−carbon double bond is the most often used radical acceptor in this type of strategy. When a carbon−carbon double bond is used for cyclization, the cyclic structure obtained is always accompanied by an additional carbon appendage. This may sometimes be an unwanted feature. Although the carbonyl chemistry constitutes a major part of the organic chemistry, it was not until recently that the radical addition to carbonyls attracted the attention of synthetic organic chemists.[2−4] When the carbonyl is used as the radical acceptor, a cyclic alcohol is obtained. This alcohol does not have the extra carbon appendage on the ring as in the olefin system mentioned above. In addition, the resulting hydroxyl group can be transformed to other useful functional groups very easily. Therefore, the radical carbonyl cyclization reaction is a potentially useful process.[2]

Scheme 1



As shown in Scheme 1,[5] Beckwith's kinetic data reveal that the k_1 value for 5-*exo* ring closure of 4-formylbutyl radical (**1**) is 8.7×10^5 s^{-1} at 80 °C. This value is comparable with the value of 1.4×10^6 s^{-1} (80 °C) for 5-*exo* ring closure of 5-hexenyl radical.[5b,6,7] In the case of 5-formylpentyl radical (**3**), k_2 is 1.0×10^6 s^{-1} (80 °C), which is faster than that for 6-*exo* ring closure of 6-heptenyl radical (4.3×10^4 s^{-1} at 80 °C).[5b,6] The problem of the two cyclization systems shown in Scheme 1 is that the ring openings of alkoxy radicals **2** ($k_{-1} = 4.7 \times 10^8$ s^{-1} at 80 °C) and **4** ($k_{-2} = 1.1 \times 10^7$ s^{-1} at 80 °C) are faster than the cyclizations. In fact, the most useful application of radical addition to carbonyl compounds relies on the controlled ring openings of the cyclized alkoxy radicals to prepare ring expansion products.[3]

To drive these kind of neutral carbonyl addition reactions to the right-hand side, one methodology is to trap or convert the cyclized alkoxy radical irreversibly. A successful demonstration of this idea is the acylsilane system developed by us.[8] Using radical **5** derived from 5-bromoacylsilane for illustration (Scheme 2), the 5-*exo* ring closure product **6** undergoes a facile radical−Brook rearrangement[9] to give α-silyloxy radical **7**. Due to the strong bonding energy of O−Si,[10] the silyl migration is

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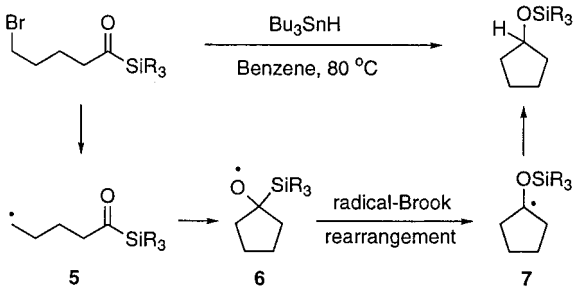
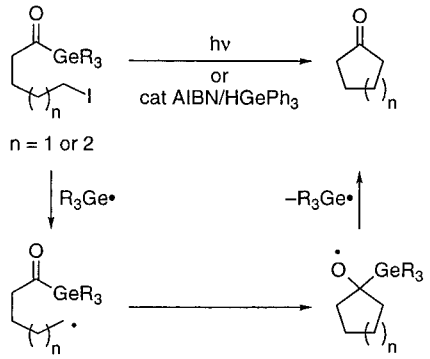
Scheme 2



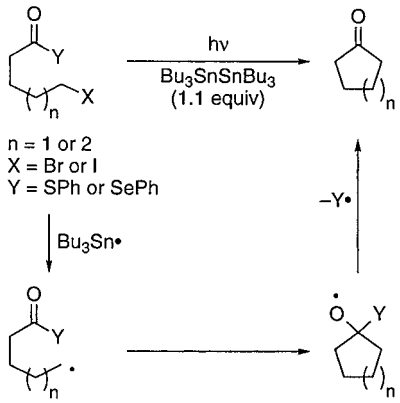
Scheme 3



most likely irreversible. Therefore, the cyclization step is essentially driven toward the right-hand side by this design. The cyclization of 4-silylcarbonylbutyl radical **5** can be considered as an equivalent of the cyclization of 4-formylbutyl radical **1**. In addition, through the radical−Brook rearrangement, the radical is relocated to the initial site of attack. Therefore, acylsilane can be regarded as a reagent equivalent of the geminal radical acceptor/radical donor synthon.[11]

Parallel to our study of acylsilanes, Curran developed the radical chemistry of acylgermanes (Scheme 3),[12] In the acylgermane system, the cyclized α-germyl alkoxy radical undergoes a β-scission reaction to obtain cyclic ketone with concomitant formation of a germyl radical which carries on the chain reaction. Reminiscent to the acylgermane system, Kim and Jon[13] recently reported the radical cyclization of thioesters and selenoesters (Scheme 4). Instead of a catalytic cycle as in the acylgermane system, the thioester and selenoester systems require the use of 1.1 equiv of hexabutylditin. The β-scission process involved in these reactions serves to drive the carbonyl cyclizations to the right-hand side. The added advantage of the acylgermane system is that it is tin free and the removal of the germanium byproduct is easy.

Scheme 4



In the case of 5-hexenyl radical cyclization, it is well-known that an alkyl substituent at C(5) severely reduces the rate of 5-*exo* cyclization.[6,14] In comparison, a recent report by Curran, Diederichsen, and Palovich[12c] on radical cyclizations of acylgermanes showed that although the cyclization rate is dependent on the germanium ligand, the steric effect of the germyl group is not obvious for 5-*exo* cyclization. This may be attributed to the longer carbon−germanium bond. Therefore, it is important to determine the size effect of the silyl group of acylsilane toward the cyclization. The feasibility of the acylsilane cyclization using primary, secondary, aryl, and vinyl radicals is also studied and described in this full account.

Results and Discussion

Synthesis of Acylsilane Substrates. Retrosynthetically, radicals such as acylsilane **5** were generated from the corresponding haloacylsilanes using the tributyltin hydride methodology. The haloacylsilanes were synthesized using method developed by Brook and Corey.[15,16] As shown in Table 1, 2-silyl-substituted 1,3-dithianes **8** were alkylated with suitable halides. The resulting aliphatic bromo 1,3-dithianes could not be stored for a long period due to the presence of a nucleophilic sulfur and electrophilic halide in the same molecule.[17] Therefore, it is best to hydrolyze the crude alkylation product directly without delay. The use of red mercuric oxide and boron trifluoride etherate in wet THF for the hydrolysis of 1,3-dithiane was generally successful.[18] However, when olefin was present as in entries 21−24, ceric ammonium nitrate (CAN) in wet acetonitrile[19] was used instead to avoid complication due to the participation of the olefin in the reaction.[20] In the cases with hindered silyl group as in dithianes **8d**[15a] and **8e**[21] (entries 4, 5,

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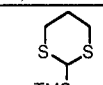
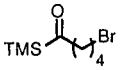
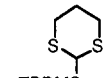
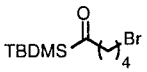
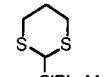
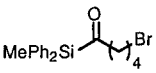
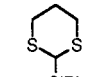
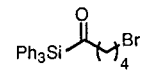
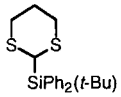
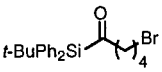
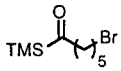
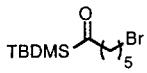
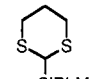
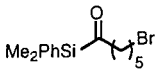
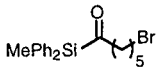
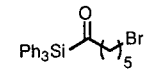
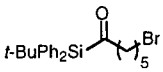
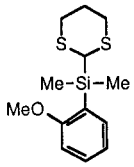
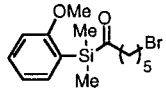
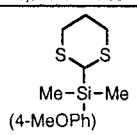
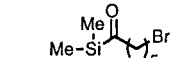
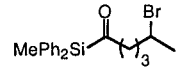
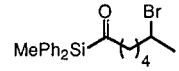
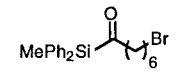
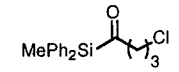
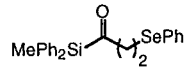
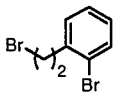
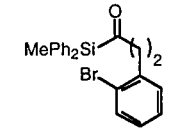
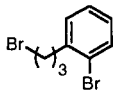
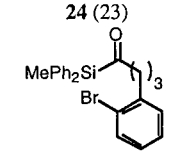
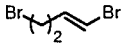
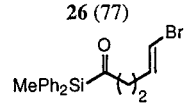
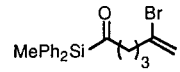
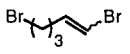
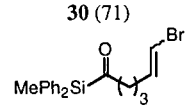
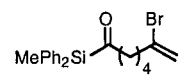
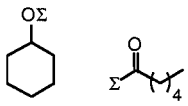
Table 1. Preparation of (Haloacyl)silanes from 2-Silyl-1,3-dithianes

entry	1,3-dithianes	halides	hydrolysis method[a]	acylsilanes (% yield)
1	 **8a**	$Br(CH_2)_4Br$ **9**	A	 **10a** (68)
2	 **8b**	**9**	A	 **10b** (54)
3	 **8c**	**9**	A	 **10c** (73)
4	 **8d**	**9**	A	 **10d** (73)
5	 **8e**	**9**	A	 **10e** (31)
6	**8a**	$Br(CH_2)_5Br$ **11**	A	 **12a** (64)
7	**8b**	**11**	A	 **12b** (70)
8	 **8f**	**11**	A	 **12f** (71)
9	**8c**	**11**	A	 **12c** (63)
10	**8d**	**11**	A	 **12d** (57)
11	**8e**	**11**	A	 **12e** (65)
12	 **8g**	**11**	B	 **12g** (60)
13	 **8h**	**11**	B	 **12h** (45)
14	**8c**	 **13**	A	 **14** (60)
15	**8c**	 **15**	A	 **16** (41)
16	**8c**	$Br(CH_2)_6Br$ **17**	A	 **18** (59)
17	**8c**	$Br(CH_2)_3Cl$ **19**	A	 **20** (77)
18	**8c**	$Br(CH_2)_2SePh$ **21**	A	 **22** (35)
19	**8c**	 **23**	A	 **24** (23)
20	**8c**	 **25**	A	 **26** (77)
21	**8c**	 **27**	B	 **28** (46)
22	**8c**	 **29**	B	 **30** (71)
23	**8c**	 **31**	B	 **32** (66)
24	**8c**	 **33**	B	 **34** (63)

[a] Method A: red HgO (2 equiv), $BF_3{\cdot}OEt_2$ (2 equiv), H_2O/THF (15/85), rt, 1 h. Method B: CAN (3 equiv), $NaHCO_3$ (1.5 equiv), H_2O/CH_3CN (1/8), −30 °C, 5 min.

10, and 11), the alkylations required the use of HMPA. In entries 19 and 21, low yields of acylsilanes **24**[8e] and **28** resulted from the elimination side reactions of dibromides **23** and **27** during alkylations.

Table 2. Radical Cyclizations of Acylsilanes Involving Primary Radicals[a]

entry	substrates	silyl groups (Σ)	products (% yield)	
1	**10a**	TMS	 **35a** (68)[b]	
2	**10b**	TBDMS	**35b** (80)	
3	**10c**	$MePh_2Si$	**35c** (82)	
4	**10d**	Ph_3Si	**35d** (91)	
5	**10e**	(*t*-Bu)Ph_2Si	**35e** (84)	
6	**12a**	TMS	 **36a** (64)[b]	**37a**[c]
7	**12d**	Ph_3Si	**36d** (59)	**37d** (26)
8[d]	**12b**	TBDMS	**36b** (51)	**37b** (38)
9	**12e**	(*t*-Bu)Ph_2Si	**36e** (30)	**37e** (63)
10	**12c**	$MePh_2Si$	**36c** (81)	**37c** (5)
11	**12f**	Me_2PhSi	**36f** (79)	**37f** (6)
12	**12g**	Me_2(2-MeOPh)Si	**36g** (52)	**37g** (32)
13	**12h**	Me_2(4-MeOPh)Si	**36h** (81)	

[a] The cyclization was performed by slow addition (6 h) of a benzene solution of tributyltin hydride (1.2−1.5 equiv) and AIBN (5 mol %) to a refluxing solution of the substrate. Equal amounts of benzene were used to prepare the two solutions, and the final concentration relative to the substrate was 0.05 M. [b] The yield was extrapolated from the yield of the corresponding benzoate derived from the silyl ether. [c] The ratio of **36a**/**37a** was determined to be 5.4/1 by GC. [d] The final concentration relative to **12b** was 0.025 M.

Cyclizations Involving Alkyl Radicals. The radical cyclization studies were generally performed by slow addition (6 h) of a benzene solution of tributyltin hydride (1.2−1.5 equiv) and AIBN (0.05 equiv) to a refluxing benzene solution of bromoacylsilane. Our results involving primary radicals are shown in Table 2. The results show that primary radicals undergo 5-*exo* cyclization very efficiently (entries 1−5). Variation of the size of the silyl group did not have a significant effect on this type of cyclizations. High yields were obtained, and we did not isolate any uncyclized reduction product. In the case of entry 1, we had difficulty isolating trimethylsilyl ether **35a** because of its volatility. To overcome this problem, we directly added benzoyl chloride (5 equiv), TBAF/THF (2.5 equiv), and triethylamine (4 equiv) at the end of cyclization and heated the reaction mixture for 3 h at 80 °C. In this way, we were able to isolate cyclopentyl benzoate in 68% yield. Therefore, the yield of **35a** should be at least 68%. Gas chromatographic analysis of the cyclization mixture derived from acyltrimethylsilane **10a** also showed that there was no uncyclized product.[22]

Contrary to 5-*exo* cyclizations, 6-*exo* cyclizations of primary radicals (entries 6−11, Table 2) are more sensitive to the change of the silyl group. Similar to that mentioned above, the 6-*exo* cyclization of acyltrimethylsilane **12a** gave the volatile cyclization product which was converted directly to cyclohexyl benzoate in 64% yield (entry 6). Therefore, the yield of cyclized silyl ether **36a** should be at least of the same value. Careful analysis of the crude reaction mixture by GC showed the presence of reduction product **37a** which was identified by comparison with an authentic sample prepared alternatively.[22,24] The ratio of **36a**/**37a** was determined to be 5.4/1 by GC. In the cases of acyltriphenylsilane **12d** (entry 7) and acyl(*tert*-butyl)dimethylsilane **12b** (entry 8), substantial amounts of straight reduction products **37d** (26%) and **37b** (38%) were also obtained. With a very bulky *tert*-butyldiphenylsilyl group (entry 9), acylsilane **12e** gave only 30% of cyclization product **36e**, and the major product was debrominated acylsilane **37e** (63%). Both acylsilanes **12d** and **12b** contain large silyl groups; however, the silyl groups are smaller than the *tert*-butyldiphenylsilyl group.[23] On the basis of these observations, it is clear that for the 6-*exo* cyclizations of acylsilanes **12**, as the size of the silyl group increases, the yield of the cyclization product decreases. Together, these results indicated that the rate of 6-*exo* cyclization of acylsilane is slower than that of the 5-*exo* cyclization.

The best two cases of this type are the cyclizations of acylsilanes **12c**[20] (entry 10) and **12f** (entry 11). Both gave ~80% of cyclized products (**36c**,**f**) with ~5% of reduction products (**37c**,**f**). As we have mentioned above the larger the size of the silyl group, the lower the yield of silyl ether **36**. Assuming that the dimethylphenylsilyl and methyldiphenylsilyl groups are larger than the trimethylsilyl group, it is surprising that both acylmethyldiphenylsilane **12c** (entry 10) and acyldimethylphenylsilane **12f** (entry 11) gave more cyclization products than acyltrimethylsilane **12a** (entry 6). We speculate that the unexpected cyclization efficiency of **12c** and **12f** is due to the presence of the phenyl group on silicon. However, with the presence of three phenyl groups on silicon as in acyltriphenylsilane **12d** (entry 7), the cyclization is less efficient due to the enhanced steric effect.

In the case of acyltriphenylgermanes, Curran, Diederichsen, and Palovich[12c] found that the 5-*exo* primary radical cyclization ($k_c = 6.4 \times 10^6$ s^{-1} at 80 °C) is faster than the 6-*exo* cyclization ($k_c = 1.3 \times 10^6$ s^{-1} at 80 °C). It was also reported that acylgermanes with triphenylgermyl group exhibit higher reactivity than those with nonaromatic germanium ligands. This was attributed to a lower carbonyl LUMO energy of acyltriphenylgermanes.[12c] The results of the cyclizations of acylsilanes shown in Table 2 are consistent with the acylgermane chemistry. However, acyltriphenylsilane **12d** (entry 7) does not cyclize as efficiently as the corresponding acyltriphenylgermane[12c] (87% cyclization).

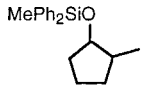
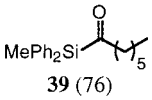
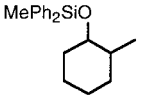
When the phenyl group on silicon contains an ortho substituent as in acylsilane **12g** (entry 12), the cyclization also is less efficient. An appreciable amount of straight reduction product **37g** (32%) was obtained along with 52% of cyclized product **36g**. In the case of acylsilane **12h** (entry 13) with a 4-methoxy group attached on the phenyl group, the cyclization gave silyl ether **36h** (81%) exclusively. This result was similar to the cyclization of acyldimethylphenylsilane **12f** (entry 11). Therefore, the

(22) Authentic straight reduction product was obtained by alkylation of **8a** with the corresponding alkyl bromide followed by hydrolysis.

(23) Hwu, J. R.; Wang, N. *Chem. Rev. (Washington, D.C.)* **1989**, *89*, 1599.

(24) Miller, J. A.; Zweifel, G. *Synthesis* **1981**, 288.

Table 3. Radical Cyclizations of Acylsilanes Involving Secondary Radicals[a]

entry	substrate	concentration (M)[b]	addition time of Bu_3SnH (h)	cyclization products (% yield)	straight reduction product (% yield)
1	**14**	0.05	6	 **38** (76)[c]	–
2	**14**	0.5	0.5	**38** (80)[c]	–
3[d]	**14**	0.5	–	**38** (94)[c]	**37c** (5)
4	**16**	0.5	0.5	–	 **39** (76)
5	**16**	0.02	2	 **40** (51)[e]	**39** (42)
6	**16**	0.009	2	**40** (57)[e]	**39** (39)

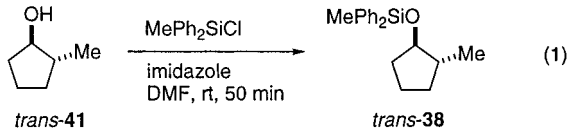
[a] The cyclization was performed by slow addition of a benzene solution of tributyltin hydride (1.2−1.3 equiv) and AIBN (5 mol %) to a refluxing benzene solution of the substrate. [b] The final concentration relative to the substrate. [c] A separable mixture of cis and trans isomers, *cis*/*trans* = 55/45. [d] The reaction was performed by directly mixing the substrate, stannane, and AIBN in benzene and heated to reflux for 0.5 h. [e] A separable mixture of cis and trans isomers, *cis*/*trans* = 3/7.

sluggish cyclization of **12g** is more likely due to the steric effect of the ortho substituent and not to the electronic effect.

5-*Exo* radical cyclizations of acylsilanes with secondary radicals were also studied (Table 3). Under the same condition as used in Table 2, acylsilane **14** (entry 1, Table 3) gave silyl ether **38** in 76% yield. Compared with the cyclization of the primary substrate **10c** (Table 2, entry 3), no apparent difference between the primary and secondary substrate is observed. We found that this reaction could be performed in a concentrated condition (0.5 M in benzene). When the tributyltin hydride solution was quickly added over 0.5 h, acylsilane **14** still gave silyl ether **38** (80%) as the only product (entry 2). Even when we mixed **14** (0.5 M in benzene), tributyltin hydride, and AIBN (5 mol %) directly and heated for 0.5 h (entry 3), we were able to isolate 52% of *cis*-**38**, 42% of *trans*-**38**, and only 5% of straight reduction product **37c**. These experiments demonstrate that the 5-*exo* cyclization of acylsilane can be performed very practically with a fairly concentrated condition in a short time.

In contrast to the 5-*exo* cyclization of acylsilane **14** (entry 2), the homologous acylsilane **16** (entry 4) gave only straight reduction product **39** (76%). Note that the conditions used in entries 2 and 4 were the same. We had to dilute the concentration and lengthen the stannane addition time (entries 5 and 6) to obtain the cyclization product. Thus, in entry 6 we were able to isolate 17% of silyl ether *cis*-**40**, 40% of *trans*-**40**, and 39% of reduction product **39**. Compared with the 6-*exo* cyclization of the primary substrate **12c** (entry 10, Table 2), the cyclization of the secondary substrate **16** is less efficient. Therefore, the 6-*exo* cyclization of acylsilane is sensitive not only to the size of the silyl group but also to the substituent at the carbon bearing the initial radical. A similar trend was also observed in the acylgermane system.[12c] This is contrary to the 5-hexenyl radical cyclization system which is less sensitive to the substituents at C(1).[6,14]

To determine the stereochemistry of the cyclized five-membered ring product **38**, we started from the commercially available *trans*-alcohol **41** and prepared an authentic sample of silyl ether *trans*-**38** via a well-known method[25] (eq 1). Therefore, the stereochemical structure



trans-**41** *trans*-**38** (1)

of *trans*-**38** was identified. ^{13}C NMR ($CDCl_3$) absorption of the methyl carbon in *trans*-**38** appeared at δ 18.1 and that of *cis*-**38** appeared at δ 14.5. The higher field absorption of the methyl carbon of *cis*-**38** indicated that the methyl group was located at a sterically more encumbered position.[26]

In the ^1H NMR ($CDCl_3$) spectra of six-membered ring silyl ether **40**, the hydrogen absorption at C-1 appeared at δ 3.75−3.90 (m, OCH) for *cis*-**40** and δ 3.24 (td, J = 10.0, 4.0 Hz, OCH) for *trans*-**40**. These values correlate reasonably well with those of *cis*- and *trans*-2-methylcyclohexanol (δ 3.82 for the *cis*-isomer and δ 3.10 for the *trans*-isomer).[27] In particular, the coupling pattern for C(1)−H of *trans*-**40** indicated that it belongs to the *trans*-diequatorial conformer. In the ^{13}C NMR spectra of **40**, the methyl carbon of *cis*-**40** appeared at δ 17.6 and that of *trans*-**40** appeared at δ 19.3. Similar to silyl ether **38**, the methyl carbon of *cis*-**40** appeared at higher field.

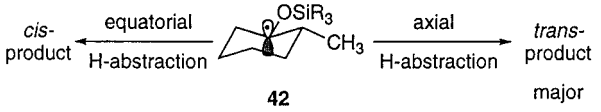
(25) Corey, E. J.; Venkateswarlu, A. *J. Am. Chem. Soc.* **1972**, *94*, 6190.
(26) Breitmaier, E.; Voelter, W. *Carbon-13 NMR Spectroscopy*; 3rd ed.; VCH: Weinhein, 1990; p 115.
(27) Iguchi, S.; Nakai, H.; Hayashi, M.; Yamamoto, H.; Maruoka, K. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3033.

Table 4. Radical Cyclizations of Acylsilanes in the Presence of Et_3B[a]

entry	substrates	amount of Et_3B (equiv)	temp (°C)	products (ratio)[d]
1[b]	**12a**	0[c]	80	**36a**/**37a** (5.4/1)
2	**12a**	1.3	rt	**36a**/**37a** (36/1)
3[e]	**12b**	0[c]	80	**36b**/**37b** (1.6/1)
4	**12b**	1.2	rt	**36b**/**37b** (4.4/1)
5[e]	**12b**	0[c]	rt	**36b**/**37b** (0.85/1)[f]
6	**12b**	1.5	80	**36b**/**37b** (2.2/1)
7	**12c**	0.18	rt	**36c**[g]

[a] A benzene solution of tributyltin hydride (1.3 equiv) was added over 2 h to a benzene solution of the substrate and triethylborane. The final concentration relative to the substrate was 0.05 M. Dry air was slowly bubbled through the reaction mixture via a syringe. [b] The reaction condition described in Table 2 was used. [c] AIBN was used for initiation. [d] The ratio was determined by GC. [e] A benzene solution of tributyltin hydride (1.2 equiv) and AIBN (5 mol %) was slowly added over 2 h to a benzene solution of the substrate. The final concentration relative to the substrate was 0.05 M. The reaction mixture was irradiated with two 100 W tungsten lamps. [f] Unreacted **12b** (32%) was observed. [g] Straight reduction product was not observed.

Scheme 5

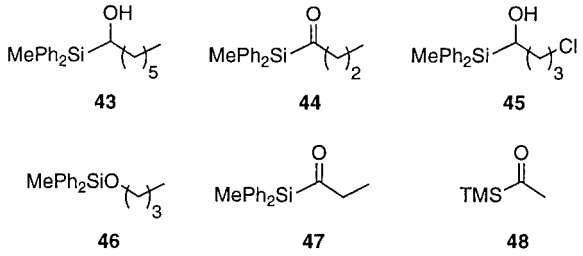


The stereochemical outcome of the cyclizations of acylsilanes **14** and **16** is determined at the hydrogen abstraction step. As shown in Scheme 5, the cyclization of **16** went through α-silyloxy radical **42** in which the methyl group preferred to adopt an equatorial position. It is well-known that the cyclohexyl radical prefers to abstract hydrogen from the axial site.[28] Therefore, axial hydrogen abstraction of radical **42** should give the *trans*-product preferentially as observed.

Effect of Triethylborane. Clive and Postema[2j] recently reported that triethylborane−stannane−air system[29] could improve the cyclization of 5-formylpentyl radical (**3**) system. On the basis of their finding, we performed radical cyclization of acylsilanes using triethylborane−air for initiation. As shown in Table 4, without triethylborane the cyclization of the primary 6-*exo* substrate **12a** at 80 °C gave cyclization product **36a**/reduction product **37a**[24] in a ratio of 5.4/1 by GC analysis (entry 1). When the triethylborane method (rt) was used (entry 2), the ratio of **36a**/**37a** improved to 36/1. Likewise, in the case with a *tert*-butyldimethylsilyl group the ratio of **36b**/**37b**[30] obtained from acylsilane **12b** (entries 3 and 4) also increased. When acylmethyldiphenylsilane **12c** was cyclized using the triethylborane method at rt (entry 6), we did not observe reduction product **37c** by GC.

To determine whether this improvement was due to the temperature or not, we performed the cyclization of **12b** at room temperature without triethylborane (entry 5). This reaction was initiated by the irradiation of two 100 W tungsten lamps in the presence of AIBN (5 mol %). The ratio of cyclization product **36b**/reduction product **37b** was 0.85/1. This result indicated that the use of triethylborane is helpful for cyclization. Interestingly, comparison of the reactions at room temperature (entry 5) and 80 °C (entry 3) showed that without triethylborane the cyclization process is preferred at higher temperature. However, when we performed the cyclization of **12b** (entry 5) at 80 °C using triethylborane−air for initiation, we found only a slight increase in the ratio of **36b**/**37b** (cf. entry 3). Therefore, the beneficial effect of triethylborane seems to operate only at lower temperature. The influence of triethylborane is small at higher temperature.

Attempted Formation of Other Ring Sizes and Intermolecular Process. To test if this method could be used to construct rings other than five- and six-membered, we examined the cyclization of acylsilanes **18**, **20**, and **22** (entries 16−18, Table 1). The chloride **20** and selenide **22** were used because we were not able to synthesize the corresponding bromides using the 1,3-dithiane strategy. Treatment of the 7-*exo* substrate **18** with tributyltin hydride (1.6 equiv) gave 68% of reduction product **39** and 23% of α-silyl alcohol **43**. Alcohol **43** was presumably derived from further reduction of acylsilane **39** with excess stannane.[31] The reaction of the 4-*exo* substrate **20** with tributyltin hydride (1.65 equiv) gave 34% of reduction product **44**, 13% of chloride **45**, 5% of silyl ether **46**, and 30% of recovered **20**. The presence of chloride **45** indicated that the rate of acylsilane carbonyl reduction by stannane is competitive to the reduction of the chloride moiety.[31,32] We do not know the origin of the silyl ether **46**. The reaction of the 3-*exo* substrate **22** with tributyltin hydride (1.3 equiv) gave 79% of reduction product **47**. Therefore, the formation of unsubstituted seven-, four- and three-membered rings is not feasible using this method.



We also examined the possibility of intermolecular coupling of alkyl radical with acylsilane. This was performed by slow addition (0.5 h) of a benzene solution of tributyltin hydride (1.2 equiv) and AIBN (5 mol %) to a refluxing benzene solution of 5 equiv of acetyltrimethylsilane (**48**) and hexadecyl bromide. The final concentration relative to the bromide was 0.5 M. Unfortunately, we did not observe any coupling product. The ^1H NMR of the crude concentrate of the reaction mixture showed that the hexadecyl bromide was completely reduced with the acylsilane **48** left intact.

Cyclizations with Aryl Radicals. An aryl radical is potentially more reactive than an alkyl radical. However, for intramolecular cyclization involving an aryl radical, the two sp^2 centers of the aryl group incorporated in the forming ring may increase the strain energy for cyclization.[33] Therefore, it is essential to test the acylsilane system with an aryl radical.

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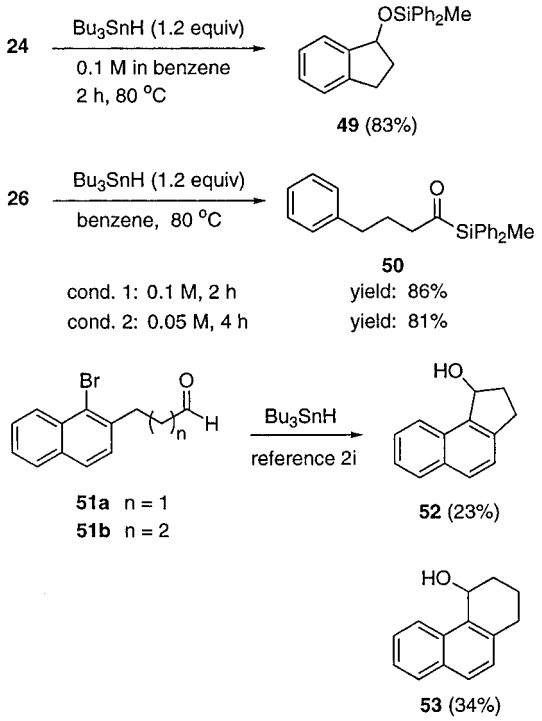
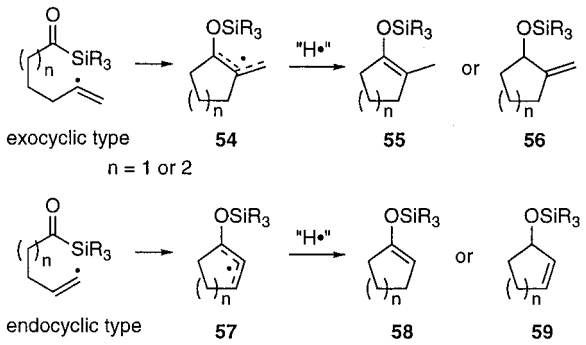
Scheme 6



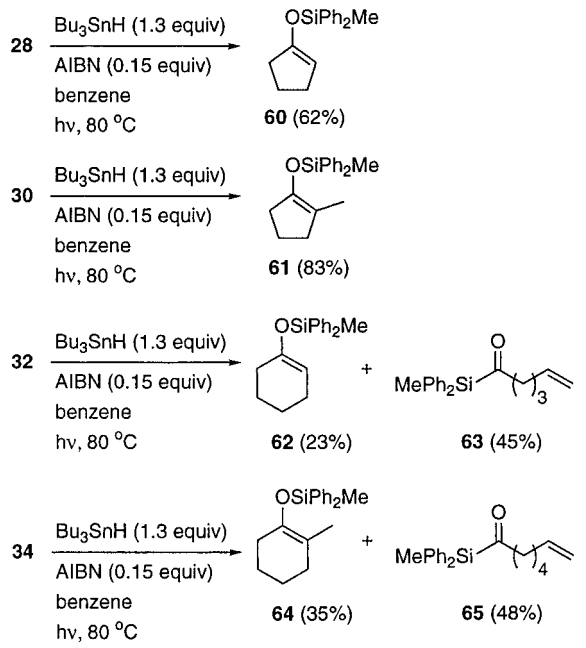
As shown in Scheme 6, the 5-*exo* substrate **24**[8e] cyclized effectively when treated with tributyltin hydride and gave silyl ether **49** in 83% yield. On the contrary, under the same condition (condition 1) the homologous acylsilane **26** gave only reduction product **50** (86%). Even when we lengthened the stannane addition rate to 4 h (condition 2) and made the concentration more dilute (0.05 M), we still obtained acylsilane **50** in 81% yield without the formation of 6-*exo* cyclization product. Previously, we noted that 1,5-hydrogen transfer involving the carbonyl α-hydrogen is a potential side reaction in our 6-*exo* cyclization system.[8b] The 1,5-hydrogen transfer process in ω-formylalkyl radical cyclizations[5b] and acylgermane cyclizations[12c] has also been reported. We believed that this might be the major process for the attempted cyclization of **26**. Grissom et al.[2i] recently reported the cyclizations of aldehydes **51**. The 5-*exo* cyclization product **52** was obtained in 23% yield from aldehyde **51a**. The acylsilane system provides an attractive alternative for the 5-*exo* cyclization. However, the acylsilane system is worse for 6-*exo* cyclization involving an aryl radical because the corresponding aldehyde **51b** gave 34% of 6-*exo* cyclization product **53** whereas acylsilane **26** gave only reduction product.

Cyclizations with Vinyl Radicals. Acylsilane cyclization involving a vinyl radical[34] provides an intriguing situation. First, there are two types of possible system. The exocyclic type (Scheme 7) having the vinyl group exocyclic to the forming ring involves one sp^2 center of the vinyl group in the forming ring. The endocyclic type having the vinyl group endocyclic to the forming ring incorporates two sp^2 centers of the vinyl group in the forming ring. Apparently, the degree of strain involved in these two systems is different. Second, cyclization followed by silyl shift provides an allylic radical as in **54** and **57**. Hydrogen abstractions of these allylic radicals are confronted with regioselectivity options. Either enol silyl ethers (**55** and **58**) or allyl silyl ethers (**56** and **59**) may be obtained.

Scheme 7



Scheme 8



Our cyclization results of vinyl radicals are summarized in Scheme 8. Initially, we had problems initiating the reaction by just heating. Therefore, we increased the amount of AIBN to 15 mol % and irradiated the reaction mixture with two 100 W tungsten lamps.[34] The two 5-*exo* cyclization systems **28** and **30** gave only cyclization products. More importantly, both cases gave regioselectively the enol silyl ethers **60**[35] (62%) and **61** (83%). Therefore, the intermediate allyl radicals prefer to abstract hydrogen at the less substituted carbon. This approach provides a unique way to prepare five-membered cyclic silyl enol ether regiospecifically.[8d]

The two 6-*exo* cyclization systems **32** and **34** behave similarly and gave low yields of enol silyl ethers **62**[36] (23%) and **64** (35%). Reduction products **63** (45%) and **65** (48%) were obtained as the major products. Presumably, 1,5-hydrogen transfer is a major competing process.

Conclusions

Acylsilanes that bear a bromo substituent at the δ and ϵ position could be easily prepared. Intramolecular

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radical cyclizations of these bromoacylsilanes were most effective for 5-*exo* cyclizations. For 6-*exo* cyclizations, the system was sensitive to the changes of the size of the silyl group and to the type of the initial radical center. 6-*Exo* cyclizations involving primary radicals were most effective when the silyl group was a methyldiphenylsilyl group. However, when a secondary radical was involved in 6-*exo* cyclization, only a moderate yield of cyclization product was obtained. Using triethylborane−air for initiation at room temperature also improved the cyclization efficiency. An aryl radical underwent 5-*exo* cyclization with acylsilane successfully. In contrast, the 6-*exo* cyclization did not occur for an aryl radical. Vinyl radicals underwent 5-*exo* cyclizations with acylsilanes successfully and afforded enol silyl ethers as the products. The corresponding 6-*exo* cyclizations only gave low yields of cyclization products.

The radical−Brook rearrangement involved in the acylsilane cyclizations not only serves to drive the reaction toward the cyclization side but also converts the cyclized oxygen radical to a carbon radical. This unique feature makes the acylsilane systems different from the ω-formylalkyl radical cyclization systems. In the latter systems cyclic alcohols are the expected products, while in the former systems silyl group protected cyclic alcohols are obtained. In more functionalized cases such as the vinyl radical cyclizations of acylsilanes, regiospecific enol silyl ethers are accessible. This type of product cannot be obtained easily via the ω-formylalkyl radical cyclizations. The cyclizations of acylsilanes are similar to acylgermanes in many respects. However, the two processes lead to different end products and are complementary. The acylgermanes cyclize to give cyclic ketones, and the reaction stops at the ketone stage.[12] The acylsilane cyclizations lead to a cyclized α-silyloxy radical and create opportunities for further manipulations.[8]

Experimental Section

Melting points are uncorrected. ^{1}H NMR spectra were recorded at 200 or 300 MHz; ^{13}C NMR spectra were recorded at 50 or 75 MHz. Tetramethysilane (δ = 0 ppm) or $CHCl_3$ (δ = 7.24 ppm) were used as internal standards, and $CDCl_3$ was used as the solvent. Benzene and THF were distilled from sodium benzophenone ketyl under N_2. HMPA was distilled over calcium hydride. The benzene used for cyclization reactions was deoxygenated by passing a gentle stream of argon through for 0.5 h before use. All reactions were performed under a blanket of N_2 or Ar. Dibromides **23**,[37] **25**,[38] **27**,[39] **29**,[40] **31**,[39] and **33**[40] were synthesized according to literature methods.

2-(Methyldiphenylsilyl)-1,3-dithiane (8c). To a solution of 2.00 g (16.7 mmol) of 1,3-dithiane in 16 mL of dry THF cooled at 0 °C was added dropwise over 20 min a solution of 1.60 M of *n*-butyllithium in hexane (11.0 mL, 17.6 mmol). The resulting solution was stirred at 0 °C for 20 min followed by the addition of 3.51 mL (16.7 mmol) of chlorodimethylphenylsilane in one portion. The resulting mixture was stirred at 0 °C for 10 min and then at rt for 30 min and partitioned between 70 mL of ether and 25 mL of water. The ether phase was washed with brine (25 mL), dried ($MgSO_4$), and concentrated in vacuo. The residual liquid was chromatographed over silica gel (eluted with hexane/ethyl acetate, 98/2) to give 3.70 g (70%) of **8c** as a white solid: mp 44−46 °C; ^{1}H NMR (200 MHz) δ 0.73 (s, 3 H), 1.91−2.19 (m, 2 H), 2.69 (dt, J = 14.0, 4.0 Hz, 2 H), 2.89 (td, J = 14.0, 4.0 Hz, 2 H), 4.20 (s, 1 H), 7.28−7.49 (m, 6 H), 7.55−7.71 (m, 4 H); ^{13}C NMR (50 MHz) δ −5.5, 26.0, 31.4, 32.8, 127.8, 129.9, 133.3, 135.1. Anal. Calcd for $C_{17}H_{20}S_2Si$: C, 64.50; H, 6.37. Found: C, 64.34; H, 6.57.

2-(*tert*-Butyldiphenylsilyl)-1,3-dithiane (8e). To a solution of 600 mg (5.00 mmol) of 1,3-dithiane in 5 mL of dry THF cooled in a dry ice−acetone bath was added dropwise over 20 min a solution of 1.50 M of *n*-butyllithium in hexane (3.60 mL, 5.40 mmol). The resulting solution was stirred at the same temperature for 20 min followed by the addition of 1.75 mL (10.0 mmol) of HMPA. The resulting solution was stirred for another 30 min at the same temperature followed by slow addition of 1.44 mL (5.50 mmol) of *tert*-butylchlorodiphenylsilane over 20 min. The resulting mixture was warmed slowly to room temperature and then stirred overnight. The reaction mixture was partitioned between 100 mL of ether and 100 mL of water. The organic layer was washed with water (100 mL) and brine (50 mL), dried ($MgSO_4$), and concentrated in vacuo. The residual oil was chromatographed over silica gel (eluted with hexane/ethyl acetate, 98/2) to give 1.35 g (75%) of **8e** as a white solid: mp 113.5−115.0 °C (EtOH); ^{1}H NMR (200 MHz) δ 1.18 (s, 9 H), 2.00−2.15 (m, 2 H), 2.70 (dt, J = 14.0, 3.6 Hz, 2 H), 2.78−3.05 (m, 2 H), 4.32 (s, 1 H), 7.35−7.48 (m, 6 H), 7.68−7.85 (m, 4 H); ^{13}C NMR (75 MHz) δ 19.2, 26.0, 28.5, 32.0, 32.7, 127.3, 129.4, 132.0, 136.2; HRMS calcd for $C_{20}H_{26}S_2Si$ *m/z* 358.1245, found 358.1256.

2-[(2-Methoxyphenyl)dimethylsilyl]-1,3-dithiane (8g). To a mixture of 290 mg (12.0 mmol) of magnesium turnings and 2 mL of THF was added a small amount of iodine and 2-bromoanisole. When the reaction was initiated, an additional portion of THF (8 mL) was added. A solution of 1.25 mL (10.0 mmol) of 2-bromoanisole in 10 mL of THF was added slowly to the above mixture in a rate as to keep a gentle reflux. The resulting mixture was stirred for another hour at room temperature and then added slowly to a solution of 6.3 mL (50 mmol) of dichlorodimethylsilane in 20 mL of THF. The reaction mixture was stirred at room temperature for 1 h, diluted with 150 mL of hexane, and filtered. The filtrate was concentrated in vacuo to remove the excess dichlorosilane, and the resulting crude chlorosilane was dissolved in 10 mL of dry THF and then cooled in an ice−water bath. To another solution of 1.20 g (10.0 mmol) of 1,3-dithiane in 10 mL of THF cooled at 0 °C was added 7.1 mL (11 mmol) of *n*-butyllithium (1.55 M in hexane). The resulting solution was added slowly to the above-mentioned crude chlorosilane solution. The resulting mixture was stirred for another 30 min and then partitioned between 100 mL of ether and 60 mL of water. The organic layer was washed with brine (20 mL), dried ($MgSO_4$), and concentrated. The residual oil was chromatographed over silica gel (eluted with hexane/dichloromethane, 9/1, 8/2, and 7/3 in sequence) to give 1.5 g (53%) of **8g** as a colorless liquid: ^{1}H NMR (300 MHz) δ 0.46 (s, 6 H), 1.90−2.16 (m, 2 H), 2.68 (dt, J = 14.0, 3.0 Hz, 2 H), 2.86 (ddd, J = 14.0, 11.0, 3.0 Hz, 2 H), 3.83 (s, 3 H), 4.10 (s, 1 H), 6.85 (d, J = 8.0 Hz, 1 H), 6.98 (t, J = 8.0 Hz, 1 H), 7.39 (t, J = 8.0 Hz, 1 H), 7.46 (d, J = 8.0 Hz, 1 H); ^{13}C NMR (50 MHz) δ −4.4, 26.1, 31.1, 33.4, 54.9, 109.6, 120.4, 122.8, 131.5, 135.7, 164.2; HRMS calcd for $C_{13}H_{20}OS_2Si$ *m/z* 284.0725, found 284.0729.

2-[(4-Methoxyphenyl)dimethylsilyl]-1,3-dithiane (8h). According to the same procedure for the synthesis of **8g**, from 0.50 g (4.2 mmol) of 1,3-dithiane we obtained 1.0 g (85%) of **8h** as a colorless liquid: ^{1}H NMR (200 MHz) δ 0.42 (s, 6 H), 1.90−2.15 (m, 2 H), 2.67 (dt, J = 14.0, 3.0 Hz, 2 H), 2.83 (ddd, J = 14.0, 11.0, 3.0 Hz, 2 H), 3.79 (s, 3 H), 3.83 (s, 1 H), 6.92 (br d, J = 9.0 Hz, 2 H), 7.51 (br d, J = 9.0 Hz, 2 H); ^{13}C NMR (50 MHz) δ −4.7, 25.9, 31.0, 33.9, 54.8, 113.5, 125.8, 135.5, 160.8; HRMS calcd for $C_{13}H_{20}OS_2Si$ *m/z* 284.0725, found 284.0719.

General Procedure for the Alkylation of 2-Silyl-1,3-dithianes with Alkyl Dibromides followed by Hydrolysis with Red Mercuric Oxide and Boron Trifluoride Etherate. To a solution of the 2-silyl-1,3-dithiane (3.0 mmol) in 6 mL of THF cooled in an ice−water bath was added dropwise over 20 min a solution of *n*-butyllithium in hexane (1.1 equiv). After another 30 min of stirring at 0 °C, the resulting solution

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was added over 45 min to a solution of the dibromide (2 equiv) in 5 mL of THF cooled at −30 °C using a dry ice−acetonitrile bath. The resulting mixture was stirred at the same temperature for 1.5 h and then partitioned between 80 mL of ether and 60 mL of water. The organic layer was washed with 50 mL of brine, dried ($MgSO_4$), and concentrated in vacuo. The residual oil was dissolved in 15 mL of wet THF (15%) followed by the addition of 1.29 g (6.0 mmol) of red mercuric oxide, 1.20 g of Celite, and 0.73 mL (6.0 mmol) of boron trifluoride etherate. The resulting mixture was stirred at room temperature for 1 h, diluted with ether (80 mL), and filtered. The filtrate was washed with brine (30 mL), dried ($MgSO_4$), and concentrated in vacuo. The residual oil was chromatographed over silica gel using hexane/ethyl acetate as eluent.

5-Bromo-1-(trimethylsilyl)pentan-1-one (10a): IR (neat) 1640 cm^{-1}; ^1H NMR (200 MHz) δ 0.21 (s, 9 H), 1.58−1.92 (m, 4 H), 2.65 (t, J = 6.0 Hz, 2 H), 3.39 (t, J = 6.0 Hz, 2 H); ^{13}C NMR (50 MHz) δ −3.4, 20.5, 32.1, 33.2, 47.0, 247.1. Anal. Calcd for $C_8H_{17}BrOSi$: C, 40.49; H, 7.22. Found: C, 40.12; H, 7.12.

5-Bromo-1-(triphenylsilyl)pentan-1-one (10d). To a solution of 2.0 g (5.3 mmol) of **8d** in 10 mL of THF cooled in an ice−water bath was added dropwise over 10 min a 1.50 M solution of *n*-butyllithium in hexane (4.0 mL, 6.0 mmol). After another 20 min of stirring, the resulting mixture was added slowly over 30 min to a solution of 1.20 mL (10.0 mmol) of **9** in 5 mL of dried HMPA cooled in an ice−water bath. The reaction mixture was stirred at 0 °C for another 1 h and then partitioned between 150 mL of ether and 100 mL of water. The organic layer was washed with water (100 mL) and brine (100 mL), dried ($MgSO_4$), and concentrated. The residual oil was dissolved in 20 mL of wet THF (15%) followed by the addition of 2.30 g (10.0 mmol) of red mercuric oxide and 2.3 g of Celite. The resulting mixture was cooled in an ice−water bath followed by the addition of 1.65 mL (13.3 mmol) of boron trifluoride etherate over 5 min. The resulting mixture was stirred at room temperature for 1 h, diluted with 40 mL of hexane/ethyl acetate (9/1), and filtered over a short pad of silica gel. The filtrate was concentrated, and the residual crude material was recrystallized from a mixture of 15 mL of hexane and 5 mL of ethyl acetate to give 1.69 g (73%) of **10d** as a white crystal: mp 133.5−134.5 °C; IR (CH_2Cl_2) 1635 cm^{-1}; ^1H NMR (200 MHz) δ 1.51−1.71 (m, 4 H), 2.73 (t, J = 6.7 Hz, 2 H), 3.27 (t, J = 6.5 Hz, 2 H), 7.30−7.50 (m, 9 H), 7.51−7.63 (m, 6 H); ^{13}C NMR (50 MHz) δ 20.8, 32.1, 33.4, 49.3, 128.2, 130.3, 131.1, 136.1, 242.2; HRMS calcd for $C_{23}H_{23}BrOSi$ m/z 422.0702, found 422.0707.

5-Bromo-1-(*tert*-butyldiphenylsilyl)pentan-1-one (10e). To a solution of 535 mg (1.5 mmol) of **8e** in 5 mL of THF cooled in an dry ice−acetone bath was added dropwise over 10 min a 1.40 M solution of *n*-butyllithium in hexane (1.2 mL, 1.7 mmol). The resulting solution was stirred for another 20 min at the same temperature followed by the addition of 1.05 mL (6.0 mmol) of HMPA and 0.20 mL (1.7 mmol) of **9**. The resulting mixture was warmed slowly to room temperature and then stirred for 1 h. The reaction mixture was partitioned between 100 mL of ether and 50 mL of water. The organic layer was washed with water (50 mL) and brine (100 mL), dried, and concentrated. The residual oil was dissolved in 15 mL of wet THF (15%) followed by the addition of 480 mg (2.4 mmol) of red mercuric oxide and 480 mg of Celite. The resulting mixture was cooled in an ice−water bath followed by the addition of 0.50 mL (4.0 mmol) of boron trifluoride etherate over 5 min. The resulting mixture was stirred at room temperature for 1 h, diluted with 50 mL of ether and filtered. The filtrate was washed with brine (20 mL), dried ($MgSO_4$), and concentrated in vacuo. The residual oil was chromatographed over silica gel (eluted with hexane/ethyl acetate, 98/2) to give 184 mg (31%) of **10e** as a pale yellow oil: IR (neat) 1635 cm^{-1}; ^1H NMR (300 MHz) δ 1.11 (s, 9 H), 1.48−1.58 (m, 2 H), 1.58−1.71 (m, 2 H), 2.50 (t, J = 6.7 Hz, 2 H), 3.25 (t, J = 6.7 Hz, 2 H), 7.32−7.45 (m, 6 H), 7.57−7.66 (m, 4 H); ^{13}C NMR (75 MHz) δ 18.4, 20.7, 27.5, 32.0, 33.2, 49.8, 128.0, 129.9, 131.7, 136.1, 244.4; HRMS calcd for $C_{21}H_{27}BrOSi$ m/z 402.1015, found 402.1019.

6-Bromo-1-[(2-methoxyphenyl)dimethylsilyl]hexan-1-one (12g). To a solution of 852 mg (3.0 mmol) of **8g** in 5 mL of THF cooled in an ice−water bath was added dropwise over 20 min a 1.55 M solution of *n*-butyllithium in hexane (2.3 mL, 3.6 mmol). After another 20 min of stirring at 0 °C, the resulting solution was added over 30 min to a solution of 2.0 mL (15 mmol) of **11** in 10 mL of THF cooled at −30 °C using a dry ice−acetonitrile bath. The resulting mixture was stirred at the same temperature for 30 min and then partitioned between 100 mL of ether and 80 mL of water. The organic layer was washed with 50 mL of brine, dried ($MgSO_4$), and concentrated in vacuo. The residual oil and 1.5 g (18 mmol) of sodium bicarbonate was mixed with 8 mL of acetonitrile and 5 mL of dichloromethane and then cooled in a dry ice−acetonitrile bath. A mixture of 4.11 g (7.50 mmol) of CAN in 8 mL of acetonitrile and 1 mL of water was added over 1 min to the above mixture. The resulting mixture was stirred for 10 min at the same temperature and then diluted with 80 mL of ether and filtered. The filtrate was washed with water (80 mL) and brine (50 mL), dried ($MgSO_4$), and concentrated. The residual oil was chromatographed over silica gel (eluted with hexane/ethyl acetate, 97/3) to give **12g** as a pale yellow oil: IR (neat) 1633 cm^{-1}; ^1H NMR (200 MHz) δ 0.42 (s, 6 H), 1.20−1.35 (m, 2 H), 1.35−1.50 (m, 2 H), 1.76 (quintet, J = 7.0 Hz, 2 H), 2.55 (t, J = 7.0 Hz, 2 H), 3.32 (t, J = 7.0 Hz, 2 H), 3.75 (s, 3 H), 6.83 (br d, J = 8.0 Hz, 1 H), 6.98 (ddd, J = 8.0, 7.0, 1.0 Hz, 1 H), 7.35−7.45 (m, 2 H); ^{13}C NMR (75 MHz) δ −4.7, 21.2, 27.8, 32.5, 33.6, 47.5, 54.9, 109.5, 120.9, 123.2, 131.8, 135.4, 163.9, 246.1; HRMS calcd for $C_{15}H_{23}BrO_2Si$ m/z 342.0651, found 342.0650.

General Procedure for Radical Cyclizations of Bromoacylsilanes 10 and 12. To a refluxing benzene (10 mL) solution of the bromoacylsilane (1 mmol) was added via syringe pump a benzene (10 mL) solution of tributyltin hydride (1.2−1.5 mmol) and AIBN (0.05 mmol) over 6 h. The resulting solution was heated at 80 °C for another hour and concentrated in vacuo. To the residual liquid was added a few drops of wet triethylamine,[41] and the resulting mixture was chromatographed over silica gel (eluted with hexane/ethyl acetate) to isolate the products.

Cyclopentyl *tert*-butyldimethylsilyl ether (35b): ^1H NMR (200 MHz) δ 0.02 (s, 6 H), 0.86 (s, 9 H), 1.40−1.55 (m, 4 H), 1.60−1.75 (m, 4 H), 4.21 (quintet, J = 5 Hz, 1 H); ^{13}C NMR (50 MHz) δ −4.7, 18.2, 23.1, 25.9, 35.7, 74.4; HRMS calcd for $C_{11}H_{24}OSi$ m/z 200.11596, found 200.1601.

Radical Cyclization of 14. *cis*- and *trans*-2-Methylcyclopentyl Methyldiphenylsilyl Ether (*cis*- and *trans*-38). To a refluxing solution of 150 mg (0.400 mmol) of **14** in 0.4 mL of benzene was added via syringe pump over 30 min a solution of 0.129 mL (0.48 mmol) of tributyltin hydride and 3.5 mg (0.022 mmol) of AIBN in 0.4 mL of benzene. The resulting solution was stirred for 2 h at 80 °C and then concentrated in vacuo. To the residual liquid was added a few drops of wet triethylamine,[41] and the resulting mixture was chromatographed over silica gel (eluted with hexane) to give 50 mg (42%) of *cis*-**38** as a colorless liquid: ^1H NMR (200 MHz) δ 0.65 (s, 3 H), 1.01 (d, J = 6.5 Hz, 3 H), 1.30−1.94 (m, 7 H), 4.16 (q, J = 4.0 Hz, 1 H), 7.26−7.46 (m, 6 H), 7.48−7.70 (m, 4 H); ^{13}C NMR (50 MHz) δ −2.4, 14.5, 21.8, 30.8, 34.7, 39.8, 127.7, 129.5, 134.4, 137.1. Anal. Calcd for $C_{19}H_{24}OSi$: C, 76.97; H, 8.16. Found: C, 76.48; H, 8.12. Further elution gave 45 mg (38%) of *trans*-**38** as a colorless liquid: ^1H NMR (200 MHz) δ 0.66 (s, 3 H), 0.89 (d, J = 6.0 Hz, 3 H), 0.99−1.21 (m, 1 H), 1.51−2.03 (m, 6 H), 3.77 (q, J = 6.0 Hz, 1 H), 7.26−7.43 (m, 6 H), 7.50−7.68 (m, 4 H); ^{13}C NMR (50 MHz) δ −2.3, 18.1, 21.4, 31.2, 34.2, 42.5, 81.3, 127.7, 129.6, 134.3, 136.9; HRMS calcd for $C_{19}H_{24}OSi$ m/z 296.1597, found 296.1597.

Radical Cyclization of 16. 1-(Methyldiphenylsilyl)-heptan-1-one (39), *cis*- and *trans*-2-Methylcyclohexyl Methyldiphenylsilyl Ether (*cis*- and *trans*-40). To a refluxing solution of 100 mg (0.257 mmol) of **16** in 22 mL of benzene was added via syringe pump over 2 h a solution of 0.090 mL (0.33 mmol) of tributyltin hydride and 3.0 mg (0.019

(41) Curran, D. P.; Chang, C.-T. *J. Org. Chem.* **1989**, *54*, 3140.

mmol) of AIBN in 7.1 mL of benzene. The resulting solution was stirred for 2 h at 80 °C and then concentrated in vacuo. To the residual liquid was added a few drops of wet triethylamine,[41] and the resulting mixture was chromatographed over silica gel (eluted with hexane followed by hexane/ethyl acetate, 99/1) to give 13 mg (17%) of *cis*-**40** as a colorless liquid: ^{1}H NMR (200 MHz) δ 0.63 (s, 3 H), 0.87 (d, J = 6.0 Hz, 3 H), 1.08−1.82 (m, 9 H), 3.75−3.90 (m, 1 H), 7.26−7.46 (m, 6 H), 7.50−7.70 (m, 4 H); ^{13}C NMR (50 MHz) δ −2.3, 17.6, 20.9, 24.7, 29.1, 33.0, 36.7, 72.5, 127.7, 129.5, 134.4, 137.2. Anal. Calcd for $C_{20}H_{26}OSi$: C, 77.37; H, 8.44. Found: C, 77.37; H, 8.19. Further elution gave 32 mg (40%) of *trans*-**40** as a colorless liquid: ^{1}H NMR (200 MHz) δ 0.65 (s, 3 H), 0.93 (d, J = 6.5 Hz, 3 H), 1.00−1.87 (m, 9 H), 3.24 (td, J = 10.0, 4.0 Hz, 1 H), 7.28−7.45 (m, 6 H), 7.52−7.68 (m, 4 H); ^{13}C NMR (50 MHz) δ −2.1, 19.3, 25.1, 25.6, 33.6, 35.8, 40.2, 78.0, 127.7, 129.6, 134.4, 137.1. Anal. Calcd for $C_{20}H_{26}OSi$: C, 77.37; H, 8.44. Found: C, 77.17; H, 8.19. Continued elution gave 31 mg (39%) of **39** as a pale yellow liquid: IR (neat) 1679, 1427, 1112 cm^{-1}; ^{1}H NMR (200 MHz) δ 0.75 (s, 3 H), 0.82 (t, J = 7.0 Hz, 3 H), 1.05−1.34 (m, 6 H), 1.45 (quintet, J = 7.0 Hz, 2 H), 2.62 (t, J = 7.0 Hz, 2 H), 7.30−7.49 (m, 6 H), 7.49−7.66 (m, 4 H); ^{13}C NMR (50 MHz) δ −5.3, 14.0, 22.1, 22.4, 28.8, 31.6, 49.7, 128.1, 130.0, 132.8, 134.9, 244.7. Anal. Calcd for $C_{20}H_{26}OSi$: C, 77.36; H, 8.44. Found: C, 76.98; H, 8.37.

General Procedure for Radical Cyclizations of 12a−c using Et_3B and Air for Initiation. To a solution of the bromide (1 mmol) and triethylborane (1.3 mmol; 1 M in hexane) in 5 mL of benzene was added via syringe pump over 2 h a solution of tributyltin hydride (1.3 equiv). During the same period, a slow stream of dry air was passed through the solution via syringe pump. The resulting solution was stirred at room temperature for another hour. The reaction mixture was then analyzed with gas chromatography using a 3.3 mm × 3 m column (10% SE30 on chromosorb W, 80−100 mesh) with a flow rate of 30 mL/min: t_R (**36a**) = 4.42 min (130 °C); t_R (**37a**) = 6.19 min (130 °C); t_R (**36b**) = 6.90 min (170 °C); t_R (**37b**) = 9.26 min (170 °C); t_R (**36c**) = 13.84 min (230 °C); t_R (**37c**) = 18.27 min (230 °C).

Radical Cyclization of 24. Methyldiphenylsilyl 1-Indanyl Ether (49). To a refluxing benzene (1.5 mL) solution of 124 mg (0.302 mmol) of **24** was added via syringe pump a benzene (1.5 mL) solution of 0.094 mL (0.36 mmol) of tributyltin hydride and 2.5 mg (0.015 mmol) of AIBN over 2 h. The resulting solution was heated at 80 °C for another 2 h and concentrated in vacuo. To the residual liquid was added a few drops of wet triethylamine,[41] and the resulting mixture was chromatographed over silica gel (eluted with hexane/ethyl acetate, 98/2) to give 82 mg (83%) of **49** as a colorless liquid: ^{1}H NMR (300 MHz) δ 0.79 (s, 3 H), 2.09 (dtd, J = 12.7, 8.0, 6.6 Hz, when irradiated at δ 5.42 collapsed into a dt, J = 12.7, 8.0 Hz, 1 H), 2.30−2.41 (m, when irradiated at δ 5.42 collapsed into a ddd, J = 12.7, 8.0, 3.7 Hz, 1 H), 2.76 (dt, J = 15.8, 8.0 Hz, 1 H), 3.04 (ddd, J = 15.8, 8.0, 3.7 Hz, 1 H), 5.42 (t, J = 6.6 Hz, 1 H), 7.15−7.25 (m, 1 H), 7.26−7.35 (m, 1 H), 7.36−7.51 (m, 8 H), 7.70−7.75 (m, 4 H); ^{13}C NMR (75 MHz) δ −2.2, 29.7, 36.2, 77.0, 124.4, 124.6, 126.3, 127.7, 127.8, 129.7, 134.4, 136.4, 142.7, 145.0. Anal. Calcd for $C_{22}H_{22}OSi$: C, 79.95; H, 6.71. Found: C, 79.84; H, 6.72.

Radical Cyclization of 28. 1-Cyclopenten-1-yl Methyldiphenylsilyl Ether (60). To a refluxing benzene (10 mL) solution of 360 mg (1.0 mmol) of **28** was added via syringe pump a benzene (10 mL) solution of 0.35 mL (1.3 mmol) of tributyltin hydride and 25 mg (0.15 mmol) of AIBN over 2 h. The resulting solution was heated at 80 °C for another 1 h. Throughout the reaction period, the reaction mixture was irradiated with two 100 W tungsten lamps. The resulting solution was concentrated in vacuo. To the residual liquid was added a few drops of wet triethylamine,[41] and the resulting mixture was chromatographed over silica gel (eluted with hexane/ethyl acetate, 99/1) to give 173 mg (62%) of **60** as a colorless liquid: IR (neat) 1637 cm^{-1}; ^{1}H NMR (300 MHz) δ 0.72 (s, 3 H), 1.80 (quintet, J = 7.2 Hz, 2 H), 2.13−2.31 (m, 4 H), 4.57 (t, J = 2.0 Hz, 1 H), 7.29−7.44 (m, 6 H), 7.54−7.68 (m, 4 H); ^{13}C NMR (75 MHz) δ −2.7, 21.2, 28.6, 33.4, 103.4, 127.8, 129.9, 134.3, 135.7, 154.7; HRMS calcd for $C_{18}H_{20}OSi$ m/z 280.1284, found 280.1295.

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Supporting Information Available: Details of compound characterization of **10b**,**c**, **12a**,**b**,**f**, **14**, **16**, **12d**,**e**,**h**, **26**, **28**, **30**, **32**, **34**, **35c**−**e**, **36c**−**h**, **37c**−**g**, **50**, **61**, **62**, **64**, and **65**; ^{1}H and ^{13}C NMR spectra of new compounds lacking analysis (34 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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