poured into saturated aqueous $NaHCO_3$ and extracted several times with hexane. The hexane extracts were washed once with saturated $NaHCO_3$ and twice with water and dried over $MgSO_4$, and the solvent was then evaporated. The resulting product could be purified by distillation or preparative GC. ^1H NMR spectra (400 MHz) of compounds isolated by the latter method include the following. **5a**: δ 0.2 (s, 9 H), 4.5 (s, 1 H), 7.4 (m, 5 H) [lit.[3b] δ 0.1 (s, 9 H), 4.31 (s, 1 H), 7.27 (s, 5 H)]. **6a**: δ -0.03 (s, 18 H), 1.46 (s, 1 H), 6.90 (d, 2 H), 7.01 (t, 1 H), 7.15 (t, 2 H) [lit.[12] (60 MHz) δ 0.04 (s, 18 H), 1.50 (1 H), 7.1 (m, 5 H). **6b**: ^1H NMR δ 0.01 (s, 18 H), 1.52 (s, 1 H), 2.18 (s, 3 H), 6.95 (d, 2 H), 7.1 (m, 2 H). **6d**: ^1H NMR δ -0.02 (s, 18 H), 1.41 (s, 1 H), 2.24 (s, 3 H), 6.79 (d, 2 H), 6.96 (d, 2 H).

Preparative-Scale Electrosynthesis of 6a. A mixture of 4.0426 g (25 mmol) of **4a** and 15 mL (12.8 g, 118 mmol) of chlorotrimethylsilane was reduced as described previously, at a constant current of 0.5 A. GC analysis indicated the yield of **6a** to be maximal at 5.4 h (ca. 100% current efficiency). Workup and distillation afforded **6a** as a water-white liquid, 4.6420 g (19.7 mmol, 78 % yield), bp 112-114 °C/18 mm (lit. bp 166 °C/99 mm[3a] and 45 °C/0.5 mm[12]). Quantitative gas chromatographic analysis (pentadecane as internal standard) indicated an 84% yield of monosilane **5a** at the midpoint of the electrolysis.

Acknowledgment. Financial support by the National Science Foundation in the form of Grant No. 85-02078 to A.J.F. and a grant for partial support of the 400-MHz NMR spectrometer used in this work is gratefully acknowledged.

Oxidative Grob Fragmentation of γ-Tributylstannyl Alcohols with a Combination of Iodosylbenzene, Dicyclohexylcarbodiimide, and Boron Trifluoride

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Received February 21, 1989

Exposure of cyclic γ-stannyl alcohols, prepared from cyclic vinyl ketones, to a combination of iodosylbenzene, dicyclohexylcarbodiimide, and boron trifluoride–diethyl ether in dichloromethane undergoes an oxidative Grob fragmentation to give unsaturated carbonyl compounds. The dicyclohexylcarbodiimide in this reaction apparently activates iodosylbenzene and decreases Lewis acidity of boron trifluoride. The fact that the iodine(III)-mediated Grob fragmentation proceeds stereospecifically suggests the fragmentation is concerted. The fragmentation, combined with conjugate addition of (tributylstannyl)lithium and reduction or alkylation, offers an efficient procedure for the reductive and alkylative ring opening of cyclic vinyl ketones. Since *cis*-benzyl ether **36**, after quenching of the reaction mixture with aqueous NH_4Cl, afforded the chlorostannane **37**, the reaction mechanism involving the formation of iodine(III) species **32** with two oxygen ligands at iodine was proposed.

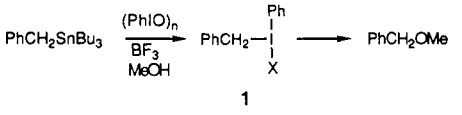
In contrast to organolithiums, magnesiums, and aluminums, tetraorganotins demonstrate only limited reactivity toward electrophiles. This is due, at least in part, to significant covalent bond character of the C–Sn bond (According to Pauling,[1] the electronegativity of Sn(IV) is 1.9 vs 2.5 for C). On the other hand, the high polarizability of this bond[2] allows for organotins to participate as versatile carbanion equivalents in ionic reactions.

Recently, we reported reactivity umpolung of organotins as well as organosilicons involving the conversion to the corresponding organoiodine(III) and organothallium(III) species. They act as carbocation equivalents and react with a variety of nucleophiles.[3-5] For example, reaction of benzyltributylstannane with iodosylbenzene (ISB) and boron trifluoride–diethyl ether in methanol affords benzyl methyl ether in 86% yield via the formation of the reactive benzyliodine(III) species **1** (Scheme I).

γ-Trialkylstannyl alcohols have been shown to be useful intermediates in organic synthesis. The 1,3-cyclization of acyclic analogues provides an efficient route to substituted cyclopropanes.[6,7] Chromic anhydride oxidation of a cyclic γ-stannyl alcohol constitutes a key step in alkylative enone transposition.[8]

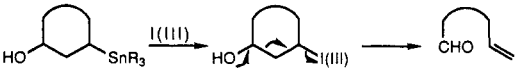
Based on the results described above, we have designed an oxidative Grob fragmentation of cyclic γ-stannyl alcohols **2** that yields unsaturated carbonyl compounds **4**. This may involve in situ generation of γ-hydroxy iodine(III) species **3** as a key intermediate by the reaction with ISB activated by Lewis acids (Scheme II).[9-11] We report herein the results in detail.

Scheme I



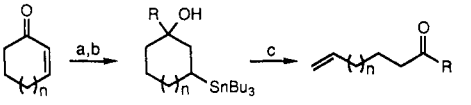
1

Scheme II



2 **3** **4**

Scheme III[a]



5a-d **6a-d**

a: R = Ph, n = 0
b: R = Ph, n = 1
c: R = n-$C_{10}H_{21}$, n = 1
d: R = Ph, n = 2

[a] Reagent: (a) Bu_3SnLi, THF; (b) PhLi or n-$C_{10}H_{21}Li$, THF; (c) DCC, ISB, BF_3–Et_2O, CH_2Cl_2.

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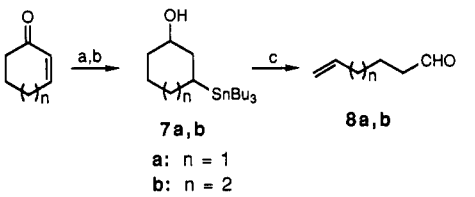
Table I. Oxidative Grob Fragmentation of γ-Stannyl Alcohols[a]

run	compd	time, h	prod.	%[b]
1	**5a** (46:54)[c]	0.5[d]	**6a**	0
2	**5a** (46:54)[c]	5	**6a**	(63)
3	**5b** (67:33)[c]	0.5[d]	**6b**	0
4	**5b** (67:33)[c]	5	**6b**	81
5	**5c** (88:12)[c]	4	**6c**	86
6	**5d** (64:36)[c]	3	**6d**	86
7	**7a** (*cis*)	1	**8a**	(74)[e]
8	**7a** (*cis*)[f]	3	**8a**	(57)
9	**7a** (*cis*)	1[d]	**8a**	(71)
10	**7a** (*trans*)	1	**8a**	(74)
11	**7b** (62:38)[c]	3	**8b**	(55)
12	**9**	0.5[d]	**10**	0[g]
13	**9**	3	**10**	18[h]
14	**12** (89:11)[i]	3	**8a**	(18)[j]

[a] Reaction conditions: DCC, ISB, BF_3–Et_2O, dichloromethane, room temperature. [b] Isolated yields (GLC yields). [c] Ratios of stereoisomers. [d] Reaction conditions: ISB, BF_3–Et_2O, dichloromethane, 0 °C. [e] *N,N'*-Dicyclohexylurea **35** was obtained in 25% yield. [f] *m*-Iodosylpyridine was used instead of ISB. [g] The alcohol **11** was obtained in 92% yield. [h] The alcohol **11** was obtained in 71% yield. [i] Ratio of cis to trans isomers. [j] A 62% of **12** was recovered unchanged.

Isoe and Nakatani independently reported the same type of 1,4-fragmentation of γ-stannyl alcohols utilizing lead tetraacetate in refluxing benzene and elegantly applied this reaction to the synthesis of brefeldin A and secologanin derivatives.[12] Lead tetraacetate mediated oxidative ring expansion of γ-stannyl alcohols was developed by Posner and co-workers.[13]

Scheme IV[a]



[a] Reagent: (a) Bu_3SnLi, THF; (b) $NaBH_4$, MeOH or lithium tri-*sec*-butylborohydride, THF; (c) DCC, ISB, BF_3–Et_2O, CH_2Cl_2.

Results and Discussion

Alkylative Ring Opening of Cyclic Vinyl Ketones. The organotin compounds **5** containing a tertiary hydroxy group were prepared from conjugated vinyl ketones (Scheme III). Michael addition of (tributylstannyl)lithium to 2-cyclopentenone in tetrahydrofuran (THF) yielded 3-(tributylstannyl)cyclopentanone;[8b] treatment with phenyllithium afforded the tertiary alcohol **5a** as a 46:54 mixture of stereoisomers in 58% yield. Similarly, stereoisomeric mixtures of **5b–d** were prepared in 76–82% yields. The relative stereochemistry of **5** was not determined, and the mixture was subjected to the oxidative ring expansion without separation.

Exposure of **5a** to ISB in the presence of boron trifluoride–diethyl ether in dichloromethane at 0 °C resulted in the disappearance of the starting material within 30 min; however, the desired olefinic ketone **6a** was not detected (Table I, run 1). The formation of byproducts is not entirely unexpected because γ-stannyl alcohols have been shown to be acid labile[6,7] and since **5a** may generate a benzylic carbocation in the presence of BF_3. In order to achieve the desired Grob fragmentation of **5a**, the Lewis acidity of BF_3 had to be decreased without lessening its ability to activate ISB. For this purpose dicyclohexylcarbodiimide (DCC) was used as an additive in the hope of decreasing the Lewis acidity of BF_3 by formation of the BF_3–DCC complex. Furthermore, we anticipated that, in analogy with the Pfitzner–Moffatt oxidation which involves the activation of dimethyl sulfoxide by the complex generated from DCC and a protic acid,[14] the BF_3–DCC complex would activate ISB.

The validity of our expectation was verified by the reaction of **5a** with a combination of DCC–ISB–BF_3, which was termed the "modified Pfitzner–Moffatt (MOPMO) conditions". Generally, the reaction was carried out as usual (see the Experimental Section) after a mixture of DCC and BF_3 was stirred in dichloromethane at room temperature for 1 h. Thus **6a** was obtained in 63% yield (run 2). Similarly, Grob fragmentation of **5b–d** under MOPMO conditions gave **6b–d** in more than 80% yields. It is noted that both stereoisomers of **5** undergo the oxidative 1,4-fragmentation.

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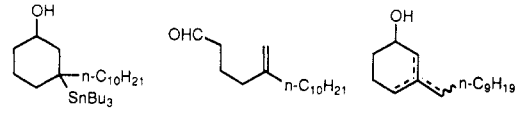
Thus, the oxidative fragmentation of **5**, combined with conjugate addition of (tributylstannyl)lithium and alkylation, offers an efficient procedure for the alkylative ring opening of cyclic vinyl ketones.

Reductive Ring Opening of Cyclic Vinyl Ketones. The *cis*-γ-tributylstannyl alcohol *cis*-**7a** was prepared from 2-cyclohexenone (Scheme IV).[15] *trans*-**7a** was prepared by the stereoselective reduction of 3-(tributylstannyl)-cyclohexanone with lithium tri-*sec*-butylborohydride in THF at −78 °C. A 62:38 stereoisomeric mixture of **7b** was synthesized from 2-cycloheptenone.

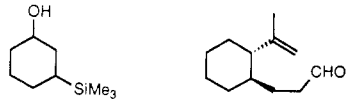
Oxidative Grob fragmentation of *trans*- and *cis*-**7a** and **7b** by the reaction with a MOPMO combination resulted in the formation of enals **8a** and **8b**, respectively. It is interesting that the cis isomer of **7a** reacts more rapidly than the conformationally flexible *trans*-**7a** (vide infra). Also, in a separate experiment (run 8), *m*-iodosylpyridine was found to be a suitable substitute for ISB: reaction of *cis*-**7a** with *m*-iodosylpyridine–DCC–BF_3 gave **8a** (57%).

In marked contrast to the case of tertiary alcohols **5**, the fragmentation of the secondary alcohol *cis*-**7a** proceeded smoothly without adding DCC and gave **8a** in 71% yield (run 9). The increased stability of *cis*-**7a** toward acids compared to that of **5** may explain the results. However, if the reaction of *cis*-**7a** in the absence of DCC is allowed to proceed for an extended period of time, decomposition of the product **8a** was observed due to the instability under acidic reaction conditions. The decomposition of **8a** did not take place under MOPMO conditions.

One of the possible decomposition pathway of **8** may be an acid-catalyzed recyclization yielding unsaturated alcohols. In the reaction of **9** with ISB and BF_3 at 0 °C for 30 min, formation of the enal **10** was not detected. The reaction afforded a mixture of cyclohexenols **11** in 92% yield (regio- and stereochemistry of that was not determined; run 12). On the other hand, **9** under MOPMO conditions gave the desired **10** in 18% yield (run 13). Andersen and Uh reported that the facile tetrachlorotin-catalyzed cyclization of **13** was completely blocked by the addition of DCC.[16]



9 **10** **11**



12 **13**

The rate of fragmentation of the silicon analogue **12** (cis:trans = 89:11) is low (run 14): exposure of **12** to a MOPMO combination at room temperature for 3 h afforded an 18% yield of **8a**, with recovery of a large amount of the starting alcohol (62%). The results can be interpreted in terms of the difference in bond energy between of C–Sn and C–Si.[17] Alternatively, the lower polarizability of the C–Si bond than that of the C–Sn bond may explain the results.[2]

The reaction sequence shown in Scheme IV provides a method for the reductive ring opening of cyclic vinyl ketones.

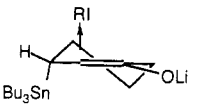
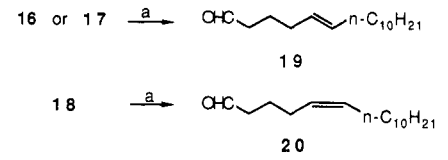


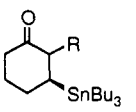
Figure 1.

Scheme V[a]

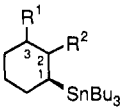


[a] Reagent: (a) DCC, ISB, BF_3–Et_2O, CH_2Cl_2.

Stereochemistry of Oxidative Grob Fragmentation. It has been shown that stereochemistry of 1,4-fragmentation reactions highly depends upon the stereochemical arrangement of nucleofugal and electrofugal groups, especially in one-step synchronous fragmentations.[18] Our attention was focused on determining whether the oxidative Grob fragmentation using ISB proceeds in a concerted or a stepwise manner. For this purpose, disubstituted cyclohexanols **16**–**18** of defined stereochemistry were synthesized.



14: R = α-n-$C_{10}H_{21}$
15: R = β-n-$C_{10}H_{21}$



16: R^1 = β-OH, R^2 = α-n-$C_{10}H_{21}$
17: R^1 = α-OH, R^2 = α-n-$C_{10}H_{21}$
18: R^1 = β-OH, R^2 = β-n-$C_{10}H_{21}$

The trans ketone **14** was prepared stereoselectively by alkylation of the lithium enolate, generated from conjugate addition of (tributylstannyl)lithium to 2-cyclohexenone in THF, with decyl iodide in 47% yield. Isomerization of **14** with NaOH in refluxing dioxane–methanol–water for 43 h gave an inseparable mixture of **14** and **15** (62:38) in 96% yield. The trans stereochemistry of **14** was determined by the $^3J(^{119}Sn–^{13}C)$ coupling constant (to *C*O): the value of 44.2 Hz of **14** is in a good agreement with that reported for trans isomers, while the value of 33.7 Hz of **15** shows the cis structure.[19a] Exclusive formation of **14** from 2-cyclohexenone is attributed to the preferred β-side attack of decyl iodide to the enolate conformer shown in Figure 1, which affords a more reactive, enolate's HOMO by the hyperconjugative interaction with C–Sn bond.[20]

Lithium aluminum hydride reduction of **14** produced a mixture of **16** and **17** (64:36) in 80% yield. Similarly, the reduction of a mixture of **14** and **15** (62:38) afforded **16**, **17**, and **18** in a 43:21:36 ratio (96% yield). Kitching and co-workers have shown that the $^3J(^{119}Sn–^{13}C)$ value serves as a valuable tool for determining the axial or equatorial nature of stannyl groups of cyclohexylstannanes.[21] A large

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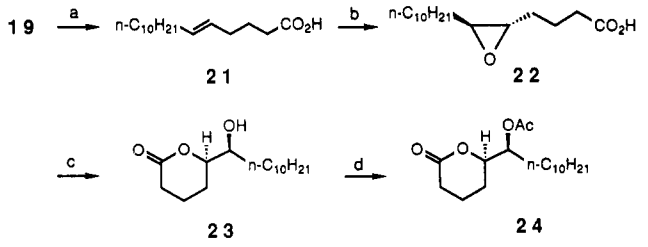
Scheme VI[a]



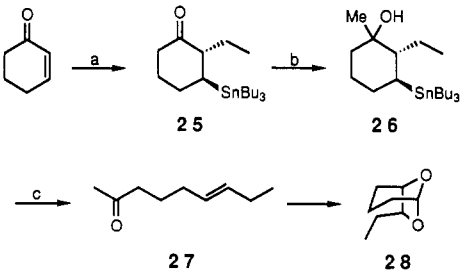
[a] Reagent: (a) $NaClO_2$, 2-methyl-2-butene, $NaH_2PO_4 \cdot 2H_2O$, *t*-BuOH; (b) *m*-CPBA, cyclohexane, toluene; (c) cyclohexane, toluene, reflux; (d) Ac_2O, pyridine.

$^3J(^{119}Sn-^{13}C)$ value (to C_3) of **16**, that is 63.5 Hz, indicates an equatorial tributylstannyl group; therefore, the trans–trans structure was assigned which is also compatible with the ^1H NMR data: δ 3.36 (dt, J = 4, 10 Hz, $W_{1/2}$ = 22.5 Hz, C_3–*H*). Similar argument leads to the trans–cis structure of **17** ($^3J(^{119}Sn-^{13}C)$ = 43.3 Hz (to C_3) and δ 3.39 (m, $W_{1/2}$ = 9 Hz, C_3–*H*)) and the cis–cis structure of **18** ($^3J(^{119}Sn-^{13}C)$ = 41 Hz (to C_3) and δ 3.78 (dt, J = 6.8, 3.9 Hz, $W_{1/2}$ = 14.5 Hz, C_3–*H*)). Moreover, cis selectivity has been observed on the reduction of *cis*-2,3-dimethylcyclohexanone with KBH_4.[22]

The iodine(III)-mediated Grob fragmentation proceeds stereospecifically (Scheme V). The 1,2-*trans*-stannanes **16** and **17** on treatment with a MOPMO combination at room temperature for 2 h gave rise to the *trans*-enal **19** selectively in 77–91% yields. The 400-MHz ^1H NMR spectra of the products did not show any signals due to the *cis*-enal **20**. On the other hand, the 1,2-*cis*-stannane **18** afforded stereoselectively **20**, albeit in low yield (45%). The stereochemistry of the fragmentation products depends upon the relative configuration between the alkyl substituent at C_2 and the tributylstannyl group at C_1. The stereochemistry of the hydroxyl group is independent of the product double-bond geometry. The results of this stereospecificity clearly show the concerted nature of the oxidative Grob fragmentation, which is in a good agreement with the results of the oxidative ring expansion of tributylstannyl lactols.[19] The stereoselective synthesis of *erythro*-6-acetoxy-5-hexadecanolide (**24**), the major component of a mosquito oviposition attractant pheromone, from the fragmentation product **19** was carried out (Scheme VI).

With these stereochemical results in hand, we have planned to synthesize *endo*-brevicomin (**28**), a component of the volatiles of several economically important bark beetles in the genera *Dendroctonus* and *Dryocetes* (Scheme VII).[23,24] Reaction of 2-cyclohexenone with Bu_3SnLi followed by EtI/HMPA gave *trans*-**25** in 69% yield. Methylation with methyllithium in THF afforded a mixture of epimeric alcohols **26** (89:11) in 62% yield. Exposure of **26** to the usual fragmentation conditions resulted in the formation of the desired *trans*-ketone **27** in 67% yield, which has been shown to produce **28** by *m*-chloroperbenzoic acid (*m*-CPBA) oxidation and *exo*-brevicomin by osmium tetraoxide oxidation.[24]

Scheme VII[a]



[a] Reagent: (a) Bu_3SnLi, THF, and then EtI, HMPA; (b) MeLi, THF; (c) DCC, ISB, BF_3–Et_2O, CH_2Cl_2.

Mechanism of Fragmentation. For the oxidative Grob fragmentation of γ-stannyl alcohols under MOPMO conditions (DCC–ISB–BF_3), a reaction mechanism involving the conversion of DCC to *N*,*N*′-dicyclohexylurea (**35**) should be considered, since the formation of **35** was confirmed in the reaction of **7a** (Table I, run 7). The first step probably involves activation of ISB by DCC–BF_3 complex **29** and gives the DCC–BF_3-activated ISB **30** as the reactive electrophile. γ-Stannyl alcohols could undergo electrophilic attack by **30** at either the hydroxyl group or the polarizable C–Sn bond. Reaction of **30** with the hydroxyl group of *trans*-γ-stannyl alcohol **31** may give iodine(III) species **32** with two oxygen ligands at iodine (Scheme VIII, path a). Synchronous fragmentation of **32** shown affords the *trans*-enal **34**, **35**, and iodobenzene. It is assumed that the oxidation of alcohols to carbonyl compounds with ISB in the presence or absence of BF_3–Et_2O probably takes place through an oxygen–iodine(III) bond formation similar to **32**.[25,26]

Alternatively, electrophilic attack of the activated ISB **30** to the electron-rich C_1–Sn bond of **31** may produce the cyclohexyliodine(III) **33** with retention of stereochemical configuration at C_1 (path b). Retention of configuration at carbon has been observed in the protodestannylation of cyclohexyltins[27] and the BF_3-catalyzed cyclization of δ-stannyl aldehydes.[28] Brominolysis of alkyltins in nonpolar solvents has been found to proceed with retention if radicals are excluded.[29] Concerted fragmentation of **33** affords the same product mixture as that derived from **32**. Both pathways are compatible with the stereochemical results obtained in this study.

To gain some insight into the mode of electrophilic attack of **30**, *cis*-benzyl ether **36**,[15] which cannot form an iodine(III) intermediate similar to **32**, was prepared and allowed to react with the MOPMO combination. Quenching of the reaction mixture with aqueous NH_4Cl afforded the chlorostannane **37** in 91% yield (Scheme IX). Reaction of **37** with butylmagnesium chloride in THF gave rise to the tributylstannane **36** (93% yield). We have reported that reaction of **36** with ISB and BF_3 in dichloromethane, after quenching with NH_4Cl, gave **37** in 91% yield.[15] These results clearly indicate that the butyl–Sn bond of **36** is much more reactive toward the electrophilic attack of **30** than the cyclohexyl–Sn bond. This selectivity is probably due to the smaller steric demands of a butyl group compared with that of a cyclohexyl

(22) Cocker, W.; McMurry, T. B. H.; Simmons, E. R. *J. Chem. Soc.* **1965**, 3022.

(23) (a) Oehlschlager, A. C.; Johnston, B. D. *J. Org. Chem.* **1987**, *52*, 940. (b) Vite, J. P.; Billings, R. F.; Ware, C. W.; Mori, K. *Naturwissenschaften* **1985**, *72*, 99. (c) Mori, K.; Sew, Y.-B. *Tetrahedron* **1985**, *41*, 3429. (d) Silverstein, R. M.; Brownlee, R. G.; Bellas, T. E.; Wood, D. L.; Browne, L. E. *Science (Washington, D.C.)* **1968**, *159*, 889.

(24) For a synthesis of **28** by silicon-directed Baeyer–Villiger reaction, see: Hudrlik, P. F.; Hudrlik, A. M.; Yimenu, T.; Waugh, M. A.; Nagendrappa, G. *Tetrahedron* **1988**, *44*, 3791.

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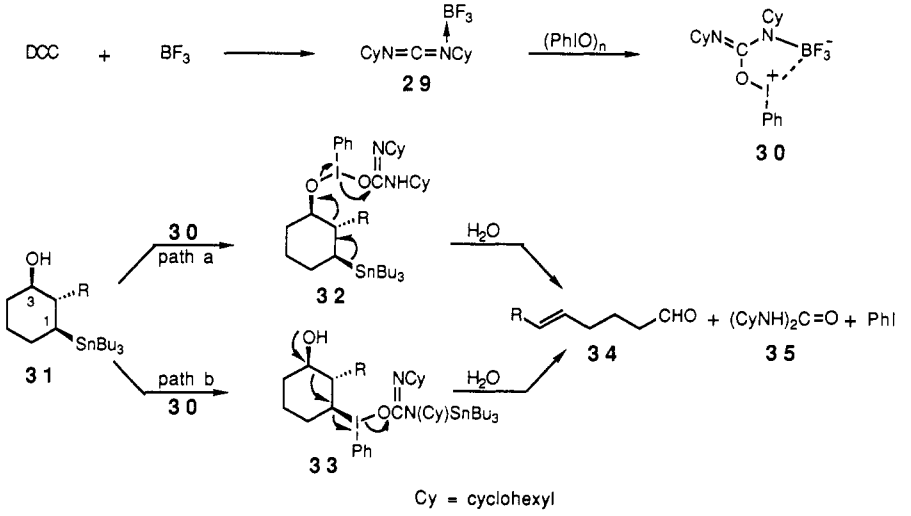
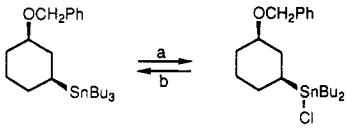
(28) Fleming, I.; Rowley, M. *Tetrahedron* **1986**, *42*, 3181.

(29) (a) Fukuto, J. M.; Jensen, F. R. *Acc. Chem. Res.* **1983**, *16*, 177. (b) Dewar, M. J. S.; Kuhn, D. R. *J. Am. Chem. Soc.* **1986**, *108*, 551.

Scheme VIII



Scheme IX[a]



[a] Reagent: (a) DCC, ISB, BF_3–Et_2O, CH_2Cl_2, and then NH_4Cl, H_2O; (b) BuMgCl, THF.

group. On the basis of these observations, it is possible to draw the conclusion that the iodine(III) species **32** with two oxygen ligands at the iodine is an intermediate in the oxidative Grob fragmentation under MOPMO conditions.

Because of the concerted nature of this fragmentation, the breaking C–C and C–Sn bonds prefer an antiperiplanar arrangement. This effect explains the reactivity differences between *trans*- and *cis*-**7a**. The iodine(III) intermediate derived from *cis*-**7a** (**38**; see Figure 2) has all the reacting orbitals properly disposed for fragmentation. On the other hand, the corresponding iodine(III) intermediate derived from *trans*-**7a**, which should be an equilibrium between conformers **39** and **40** (see Figure 2), cannot adopt such an arrangement. Consequently, *cis*-**7a** undergoes the oxidative Grob fragmentation more rapidly.

Conclusions

We have developed a method for the oxidative Grob fragmentation of cyclic γ-stannyl alcohols utilizing a MOPMO combination, in which DCC activates ISB and decreases Lewis acidity of BF_3. The fragmentation, combined with conjugate addition of (tributylstannyl)lithium and reduction or alkylation, offers an efficient procedure for the reductive and alkylative ring opening of cyclic vinyl ketones. The products, olefinic carbonyl compounds of defined stereochemistry, are versatile intermediates in organic synthesis.

Experimental Section

IR spectra were recorded on either a JASCO A-202 or Shimadzu IR-27G spectrometer. ^1H NMR were recorded in $CDCl_3$ on either a JEOL JNM-GX 400, a JEOL JNM-FX 100, a JEOL JNM-PMX 60, or a Hitachi R-22M (90 MHz) spectrometer. ^{13}C NMR were taken in $CDCl_3$ on a JEOL JNM-GX 400 or a JEOL JNM-FX 100 spectrometer. Chemical shifts were reported in parts per million (ppm) downfield from internal Me_4Si. Mass spectra (MS) were obtained on a JEOL JMS-OISG or a Hitachi M-60 spectrometer.

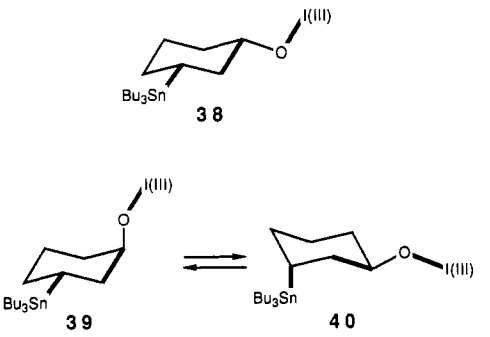


Figure 2.

Reactions were performed under a nitrogen or argon atmosphere. THF was distilled from sodium benzophenon ketyl under nitrogen. Methanol and dichloromethane were dried over CaH_2 and distilled. Analytical gas chromatography (GC) was carried out on a Shimadzu Model GC-4CM or GC-4CPF gas chromatograph with 5% FFAP or 3% Silicone OV-17 on Chromosorb W. Preparative GC was performed on a Varian Aerograph Model 920 gas chromatograph. Kieselgel 60 (Merck, 230–400 mesh) and alumina (Woelm, neutral) were used for flash chromatography. Thin-layer chromatography (TLC) was carried out on Kieselgel 60 F254 (Merck).

Iodosylbenzene and *m*-iodosylpyridine were prepared from iodobenzene diacetate and *m*-iodopyridine dichloride, respectively.[30]

Reaction of Benzyltributylstannane with Iodosylbenzene and Boron Trifluoride. To a suspension of benzyltributylstannane (39 mg, 0.10 mmol) and ISB (26 mg, 0.12 mmol) in 0.4 mL of MeOH was added BF_3–Et_2O (0.12 mmol) at room temperature, and the mixture was stirred for 1 h. Analytical GC showed the formation of benzyl methyl ether in 86% yield.

Conjugate Addition of (Tributylstannyl)lithium to Cyclic Vinyl Ketones. The conjugate addition of (tributylstannyl)lithium was carried out according to the procedure developed by Still.[8b] A cyclic vinyl ketone (2 mmol) was added dropwise to a THF solution of (tributylstannyl)lithium (0.29 M solution, 2 mmol) at −78 °C. After being stirred for 30 min at that temperature, the reaction mixture was quenched with an aqueous NH_4Cl solution and extracted with diethyl ether. The organic layer was washed with brine, dried over sodium sulfate, and concentrated in vacuo to give an oil. The crude product was purified by flash chromatography (15:1 hexane/ethyl acetate) to give a tributylstannyl ketone.

(30) (a) Pausacker, K. H. *J. Chem. Soc.* **1953**, 107. (b) Saltzman, H.; Sharefkin, J. G. *Organic Syntheses*; Wiley: New York, 1973; Collect. Vol. 5, p 658. (c) Magidson, O. J.; Lossik, J. B. *Chem. Ber.* **1934**, *67*, 1329.

3-(Tributylstannyl)cyclopentanone: colorless oil; 74% yield; IR (film) 1740, 1460, 1375, 1145 cm^{-1}; ^1H NMR (90 MHz) δ 0.7–1.1 (15 H), 1.1–2.0 (15 H), 2.0–2.6 (4 H); MS m/z 374 (M^+), 317, 235, 179 (base peak), 121; HRMS calcd for $C_{17}H_{34}OSn$ (M^+) 374.1631, found 374.1578.

3-(Tributylstannyl)cyclohexanone:[8b] colorless oil; 74% yield; IR (film) 1715, 1460, 1230 cm^{-1}; ^1H NMR (100 MHz) δ 0.6–1.1 (15 H), 1.1–2.2 (17 H), 2.2–2.6 (4 H).

3-(Tributylstannyl)cycloheptanone: colorless oil; 67% yield; IR (film) 1700, 1460, 1380, 1075, 660 cm^{-1}; ^1H NMR (90 MHz) δ 0.7–1.1 (15 H), 1.1–2.3 (19 H), 2.35–2.85 (4 H); MS m/z 402 (M^+), 345 (base peak), 231, 179, 121; HRMS calcd for $C_{19}H_{38}OSn$ (M^+) 402.1944, found 402.1916.

3-Decyl-3-(tributylstannyl)cyclohexanone: colorless oil; 67% yield; IR (film) 1715, 1460, 1375 cm^{-1}; ^1H NMR (90 MHz) δ 0.7–1.1 (18 H), 1.1–2.6 (38 H); MS m/z 528 (M^+), 471, 291, 235, 175, 110 (base peak); HRMS calcd for $C_{28}H_{56}OSn$ (M^+) 528.3353, found 528.3388.

Preparation of 1-Phenyl-3-(tributylstannyl)cyclopentanol (5a). To a solution of 3-(tributylstannyl)cyclopentanone (394 mg, 1.06 mmol) in 4 mL of THF was added dropwise phenyllithium (2.4 M cyclohexane–diethyl ether solution, 0.88 mL, 2.11 mmol) at −78 °C, and the mixture was stirred for 45 min. The reaction mixture was quenched with brine and extracted with diethyl ether. The organic layer was dried over sodium sulfate and concentrated. In order to separate the desired tertiary alcohol **5a** from the remaining ketone, the crude product was reduced with $LiAlH_4$ in THF. Purification with flash chromatography (15:1 hexane/ethyl acetate) afforded **5a** (276 mg, 59%) as a 46:54 mixture of stereoisomers. Major isomer of **5a**: R_f 0.42 (9:1 hexane/ethyl acetate); ^1H NMR (400 MHz) δ 0.78–0.95 (15 H), 1.26–1.57 (14 H), 1.81–2.30 (6 H), 7.24 (1 H, m), 7.35 (2 H, m), 7.49 (2 H, m); MS m/z 395 (M^+ − Bu, base peak), 235, 179, 143; HRMS calcd for $C_{19}H_{31}OSn$ (M^+ − Bu) 395.1396, found 395.1384. Minor isomer of **5a**: R_f 0.5 (9:1 hexcane/ethyl acetate); ^1H NMR (400 MHz) δ 0.80–0.91 (15 H), 1.27–1.62 (15 H), 1.93–2.09 (4 H, m), 2.44 (1 H, dd, J = 10.0, 13.4 Hz), 7.23 (1 H, m), 7.34 (2 H, m), 7.49 (2 H, m); MS m/z 395 (M^+ − Bu), 377, 235, 179, 143 (base peak); HRMS calcd for $C_{19}H_{31}OSn$ (M^+ − Bu) 395.1396, found 395.1361.

Preparation of 1-Phenyl-3-(tributylstannyl)cyclohexanol (5b). 3-(Tributylstannyl)cyclohexanone (98 mg, 0.25 mmol) was treated with phenyllithium as in the preparation of **5a** to give an oil. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give **5b** (92 mg, 78%) as a 67:33 mixture of stereoisomers: IR (film) 3420, 1460, 1380, 760, 700 cm^{-1}; ^1H NMR (400 MHz) δ 0.80–0.94 (15 H), 1.25–1.95 (22 H), 7.24 (1 H, m), 7.36 (2 H, m), 7.50 (2 H, m); MS m/z 409 (M^+ − Bu), 391, 235, 158 (base peak); HRMS calcd for $C_{20}H_{33}OSn$ (M^+ − Bu) 409.1553, found 409.1569.

Preparation of 1-Decyl-3-(tributylstannyl)cyclohexanol (5c). 3-(Tributylstannyl)cyclohexanone (500 mg, 1.29 mmol) was treated with decyllithium (1.09 M diethyl ether solution) as in the preparation of **5a** to give an oil. The crude product was purified by flash chromatography (15:1 hexane/ethyl acetate) to give **5c** (557 mg, 82%) as an 88:12 mixture of stereoisomers: Major isomer of **5c**: R_f 0.32 (19:1 hexane/ethyl acetate); IR (film) 3440, 1460, 1375, 960 cm^{-1}; ^1H NMR (400 MHz) δ 0.81 (6 H), 0.88 (3 H, t, J = 7 Hz), 0.89 (9 H, t, J = 7 Hz), 1.22–1.83 (40 H); ^{13}C NMR (100 MHz) δ 71.0 ($J(^{119}Sn-^{13}C)$ = 51.9 Hz), 44.5, 41.9 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 36.9, 31.9, 30.9 ($J(^{119}Sn-^{13}C)$ = 15.9 Hz), 30.4, 29.7, 29.7, 29.4 ($J(^{119}Sn-^{13}C)$ = 19.5 Hz), 27.6 ($J(^{119}Sn-^{13}C$ = 53.1 Hz), 24.0 ($J(^{119}Sn-^{13}C)$ = 58.6 Hz), 22.9, 22.7, 19.0 ($J(^{119}Sn-^{13}C)$ = 342.5 Hz), 14.1, 13.7, 7.7 ($J(^{119}Sn-^{13}C)$ = 304.0 Hz); MS m/z 473 (M^+ − Bu), 455 (base peak), 251, 235, 179; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ − Bu) 473.2805, found 473.2815. Minor isomer of **5c**: R_f 0.22 (19:1 hexane/ethyl acetate); IR (film) 3370, 1460, 1380, 905, 735 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H), 0.88 (3 H, t, J = 7 Hz), 0.89 (9 H, t, J = 7 Hz), 1.20–1.88 (40 H); ^{13}C NMR (100 MHz) δ 72.8 ($J(^{119}Sn-^{13}C)$ = 59.2 Hz), 43.3 ($J(^{119}Sn-^{13}C)$ = 15.9 Hz), 39.1, 36.6, 31.9, 30.6 ($J(^{119}Sn-^{13}C)$ = 15.9 Hz), 30.3, 29.8, 29.7, 29.4 ($J(^{119}Sn-^{13}C)$ = 19.5 Hz), 27.6 ($J(^{119}Sn-^{13}C)$ = 51.9 Hz), 25.9 ($J(^{119}Sn-^{13}C)$ = 61.0 Hz), 22.8, 22.7, 21.1 ($J(^{119}Sn-^{13}C)$ = 336.9 Hz), 14.1, 13.7, 7.9 ($J(^{119}Sn-^{13}C)$ = 304.5 Hz); MS m/z 473 (M^+ − Bu), 455, 251 (base peak), 235, 177, 81; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ − Bu) 473.2805, found 473.2820.

Preparation of 1-Phenyl-3-(tributylstannyl)cycloheptanol (5d). 3-(Tributylstannyl)cycloheptanone (102 mg, 0.27 mmol) was treated with phenyllithium as in the preparation of **5a** to give an oil. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give **5d** (100 mg, 82%) as a 64:36 mixture of stereoisomers: Major isomer of **5d**: R_f 0.46 (9:1 hexane/ethyl acetate); IR (film) 3450, 1460, 1375, 755, 700 cm^{-1}; ^1H NMR (400 MHz) δ 0.81 (6 H), 0.88 (9 H, t, J = 7 Hz), 1.23–2.10 (24 H), 7.23 (1 H, m), 7.33 (2 H, m), 7.49 (2 H, m); MS m/z 423 (M^+ − Bu), 405, 291, 235, 172 (base peak), 105; HRMS calcd for $C_{21}H_{35}OSn$ (M^+ − Bu) 423.1710, found 423.1711. Minor isomer of **5d**: R_f 0.33 (9:1 hexane/ethyl acetate); IR (film) 3370, 1460, 1375, 1025, 700 cm^{-1}; ^1H NMR (400 MHz) δ 0.78 (6 H), 0.86 (9 H, t, J = 7 Hz), 1.21–2.09 (22 H), 2.19 (1 H, ddd, J = 15, 10, 1.5 Hz), 2.44 (1 H, d, J = 15 Hz), 7.23 (1 H, m), 7.32 (2 H, m), 7.49 (2 H, m); MS m/z 480 (M^+), 423, 405, 291, 235, 172 (base peak), 105; HRMS calcd for $C_{25}H_{44}OSn$ (M^+) 480.2414, found 480.2435.

Reaction of 5 with Iodosylbenzene and Boron Trifluoride (runs 1 and 3 in Table I). To a suspension of **5a** (30 mg, 0.067 mmol), ISB (18 mg, 0.080 mmol), and octadecane (internal standard) in 0.6 mL of dichloromethane was added a solution of BF_3–Et_2O (11 mg, 0.080 mmol) in 0.2 mL of dichloromethane at 0 °C, and the mixture was stirred for 30 min at 0 °C. Analytical TLC (9:1 hexane/ethyl acetate) showed the disappearance of **5a**; however, the desired olefinic ketone **6a** was not detected by analytical GC (FFAP). Reaction of **5b** with ISB and BF_3–Et_2O gave a similar result.

General Procedure for Grob Fragmentation of 5 under MOPMO Conditions. Boron trifluoride–diethyl ether (0.12 mmol) was added to a solution of DCC (0.12 mmol) in 0.5 mL of dichloromethane, and the mixture was stirred for 1 h at room temperature. The mixture was added to a suspension of **5** (0.1 mmol) and ISB (0.12 mmol) in 0.5 mL of dichloromethane at 0 °C, and the mixture was stirred under the conditions described in Table I. The reaction mixture was quenched with brine and extracted with dichloromethane. The organic layer was dried over sodium sulfate and concentrated under an aspirator vacuum. The crude product was purified by preparative TLC to give **6**. The yield of **6** was determined by gas chromatography or by isolation of the pure product.

4-Benzoyl-1-butene (6a):[31] run 2; oil; 63% yield (determined by analytical GC (FFAP)); IR (film) 3070, 1690, 1640, 1600, 1450, 1205, 915, 740, 690 cm^{-1}; ^1H NMR (90 MHz) δ 2.54 (2 H, m), 3.08 (2 H, t, J = 8 Hz), 5.09 (2 H, m), 5.94 (1 H, m), 7.48 (3 H, m), 7.94 (2 H, m); MS m/z 160 (M^+), 105 (base peak), 77; HRMS calcd for $C_{11}H_{12}O$ (M^+) 160.0888, found 160.0896.

5-Benzoyl-1-pentene (6b):[32] run 4; oil; 81% isolated yield (preparative TLC (17:2 hexane/ethyl acetate)); IR (film) 3060, 1680, 1640, 1600, 1450, 910, 755, 690 cm^{-1}; ^1H NMR (60 MHz) δ 1.05–2.40 (4 H), 2.97 (2 H, t, J = 9 Hz), 5.02 (2 H, m), 5.80 (1 H, m), 7.33–8.02 (5 H, m); MS m/z 174 (M^+), 120, 105 (base peak), 77; HRMS calcd for $C_{12}H_{14}O$ (M^+) 174.1044, found 174.1033.

6-Oxo-1-hexadecene (6c): run 5; oil; 86% isolated yield (preparative TLC (40:1 hexane/ethyl acetate)); IR (film) 1715, 1640, 1460, 1380, 910 cm^{-1}; ^1H NMR (90 MHz) δ 0.88 (3 H), 1.1–1.9 (18 H), 2.07 (2 H, m), 2.40 (4 H), 5.00 (2 H, m), 5.73 (1 H, m); MS m/z 238 (M^+), 169 (base peak), 112, 84, 58; HRMS calcd for $C_{16}H_{30}O$ (M^+) 238.2295, found 238.2294.

6-Benzoyl-1-hexene (6d):[33] run 6; oil; 86% isolated yield (preparative TLC (9:1 hexane/ethyl acetate)); IR (film) 1685, 1640, 1595, 1450, 1220, 910, 750, 730, 690 cm^{-1}; ^1H NMR (90 MHz) δ 1.22–1.92 (4 H), 2.13 (2 H, m), 2.99 (2 H, t, J = 7 Hz), 5.00 (2 H, m), 5.82 (1 H, m), 7.50 (3 H, m), 7.98 (2 H, m); MS m/z 188 (M^+), 120, 105 (base peak), 77; HRMS calcd for $C_{13}H_{16}O$ (M^+) 188.1202, found 188.1210.

Reduction of 3-(Tributylstannyl)cyclohexanone with Sodium Borohydride. To a solution of 3-(tributylstannyl)-cyclohexanone (1.79 g, 4.62 mmol) in 25 mL of MeOH was added $NaBH_4$ (349 mg, 9.24 mmol) at 0 °C, and the reaction mixture was stirred for 30 min at the same temperature. Acetone (3 mL) was added, and the mixture was stirred at room temperature for

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15 min. The solvent was removed, and the mixture was extracted with diethyl ether. The organic layer was dried over sodium sulfate and concentrated. The crude product was separated by flash chromatography (8:2 hexane/ethyl acetate) to afford 1.47 g of *cis*-**7a** (82%) and 0.18 g of *trans*-**7a** (10%). *cis*-**7a**: oil; IR (film) 3350, 1460, 1090, 1035, 950, 735, 665 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H, m), 0.89 (9 H, t, J = 7.3 Hz), 1.22–1.51 (18 H, m), 1.79 (2 H, m), 2.05 (2 H, m), 3.49 (1 H, m, $W_{1/2}$ = 20 Hz); ^{13}C NMR (25 MHz) δ 72.4 ($J(^{119}Sn-^{13}C)$ = 68.9 Hz), 40.9 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 36.5, 30.5 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 29.4 ($J(^{119}Sn-^{13}C)$ = 19.1 Hz), 27.7, 27.6 ($J(^{119}Sn-^{13}C)$ = 52.8 Hz), 22.6 ($J(^{119}Sn-^{13}C)$ = 333 Hz), 13.6, 8.0 ($J(^{119}Sn-^{13}C)$ = 306 Hz); MS m/z 333 (M^+ – Bu), 251, 235, 177 (base peak); HRMS calcd for $C_{14}H_{29}OSn$ (M^+ – Bu) 333.1241, found 333.1249. *trans*-**7a**: oil; IR (film) 3370, 1465, 1080, 970, 735, 665 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H, m), 0.89 (9 H, t, J = 7.3 Hz), 1.26–1.90 (22 H), 3.84 (1 H, m, $W_{1/2}$ = 9.5 Hz); ^{13}C NMR (25 MHz) δ 67.9 ($J(^{119}Sn-^{13}C)$ = 41.0 Hz), 38.6 ($J(^{119}Sn-^{13}C)$ = 13.2 Hz), 34.2, 30.8 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 29.4 ($J(^{119}Sn-^{13}C)$ = 19.1 Hz), 27.6 ($J(^{119}Sn-^{13}C)$ = 51.3 Hz), 23.3 ($J(^{119}Sn-^{13}C)$ = 42.5 Hz), 19.7 ($J(^{119}Sn-^{13}C)$ = 341 Hz), 13.6, 8.4 ($J(^{119}Sn-^{13}C)$ = 302 Hz); MS m/z 390 (M^+), 331, 235, 179 (base peak), 121; HRMS calcd for $C_{18}H_{38}OSn$ (M^+) 390.1944, found 390.1941.

Reduction of 3-(Tributylstannyl)cyclohexanone with Lithium Tri-*sec*-butylborohydride. To a soltuion of lithium tri-*sec*-butylborohydride (1 M THF solution, 2.89 mL, 2.89 mmol) was added dropwise a solution of 3-(tributylstannyl)cyclohexanone (560 mg, 1.45 mmol) in 0.7 mL of THF at –78 °C. After being stirred for 30 min at the temperature, the reaction mixture was quenched by the addition of 2 mL of acetone, poured into brine, and extracted with diethyl ether. The organic layer was dried over sodium sulfate and concentrated. The crude product was purified by alumina column chromatography (8:2 hexane/ethyl acetate), affording 411 mg of *trans*-**7a** (73%) and 31 mg of *cis*-**7a** (5%).

Reduction of 3-(Tributylstannyl)cycloheptanone with Sodium Borohydride. 3-(Tributylstannyl)cycloheptanone (619 mg, 1.54 mmol) was treated with $NaBH_4$ (117 mg, 3.1 mmol) as in the preparation of *cis*-**7a**. The crude product was purified by flash chromatography (6:1 hexane/ethyl acetate) to give **7b** (471 mg, 76%) as a 62:38 mixture of stereoisomers: oil; IR (film) 3330, 1460, 1375, 1025 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H, m), 0.89 (9 H), 1.24–2.17 (24 H, m), 3.69 (0.38 H, m), 3.98 (0.62 H, m); MS m/z 347 (M^+ – Bu), 251, 235, 179 (base peak); HRMS calcd for $C_{15}H_{31}OSn$ (M^+ – Bu) 347.1396, found 347.1392.

Reduction of 3-Decyl-3-(tributylstannyl)cyclohexanone with Sodium Borohydride. 3-Decyl-3-(tributylstannyl)cyclohexanone (410 mg, 0.78 mmol) was treated with $NaBH_4$ (59 mg, 1.6 mmol) as in the preparation of *cis*-**7a**. The crude product was purified by flash chromatography (17:3 hexane/ethyl acetate) to give a mixture of stereoisomers of **9** (365 mg, 89%): oil; IR (film) 3300, 1460, 1375, 1045, 540 cm^{-1}; ^1H NMR (60 MHz) δ 0.7–2.5 (57 H), 3.60 (1 H, m); MS m/z 473 (M^+ – Bu), 291 (base peak), 235, 179, 81; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ – Bu) 473.2804, found 473.2793.

Preparation of 3-(Trimethylsilyl)cyclohexanol (12). According to the procedure of Kitching,[21d] an 89:11 cis/trans mixture of **12** was prepared from 2-cyclohexen-1-one by the conjugate addition of (trimethylsilyl)lithium and $LiAlH_4$ reduction of the resulting 3-(trimethylsilyl)cyclohexanone.

Grob Fragmentation of *cis*-7a under MOPMO Conditions (run 7 in Table I). According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, the γ-tributylstannyl alcohol ***cis*-7a** (59 mg, 0.15 mmol) was treated with ISB (40 mg, 0.18 mmol), BF_3–Et_2O (26 mg, 0.18 mmol), and DCC (38 mg, 0.18 mmol) at room temperature. The yield of 5-hexenal (**8a**) was determined by analytical GC (FFAP; 74% yield after 1 h, 72% yield after 4 h) with tridecane as an internal standard. The formation of *N,N'*-dicyclohexylurea (**35**) (25%) was detected by analytical GC (Silicone OV-17). A pure sample of **8a** was obtained by preparative GC, and the structure was determined by the comparison with the authentic sample, prepared from 1-hexen-6-ol according to the reported procedure.[34] **8a**: ^1H NMR (400 MHz) δ 1.74 (2 H, quint, J = 7 Hz), 2.11 (2 H, q, J = 7 Hz), 2.45 (2 H, dt, J = 1.5, 7 Hz), 5.01 (2 H, m), 5.77 (1 H, m), 9.78 (1 H, t, J = 1.5 Hz); MS m/z 98 (M^+).

Grob Fragmentation of *cis*-7a with *m*-Iodosylpyridine (run 8 in Table I). According to the general procedure, the alcohol *cis*-**7a** (70 mg, 0.18 mmol) was treated with *m*-iodosylpyridine (48 mg, 0.22 mmol), DCC (44 mg, 0.22 mmol), and BF_3–Et_2O (31 mg, 0.22 mmol) at room temperature for 3 h. Analytical GC (FFAP) showed the formation of **8a** (57%).

Grob Fragmentation of *cis*-7a with Iodosylbenzene and Boron Trifluoride (run 9 in Table I). To a suspension of *cis*-**7a** (45 mg, 0.12 mmol) and ISB (30 mg, 0.14 mmol) in 1 mL of dichloromethane was added a solution of BF_3–Et_2O (20 mg, 0.14 mmol) in 0.2 mL of dichloromethane at 0 °C, and the reaction mixture was stirred at 0 °C. The yield of **8a** was determined by analytical GC (FFAP; 71% yield after 1 h, 65% yield after 2 h, 48% yield after 3 h).

Grob Fragmentation of *trans*-7a under MOPMO Conditions (run 10 in Table I). According to the general procedure, *trans*-**7a** (60 mg, 0.15 mmol) was treateed with ISB (41 mg, 0.18 mmol), BF_3–Et_2O (26 mg, 0.18 mmol), and DCC (38 mg, 0.18 mmol) at room temperature for 1 h. Analytical GC showed the formation of **8a** (74%).

Grob Fragmentation of 7b under MOPMO Conditions (run 11 in Table I). According to the general procedure, **7b** (84 mg, 0.21 mmol) was treated with ISB (55 mg, 0.25 mmol), BF_3–Et_2O (35 mg, 0.25 mmol), and DCC (77 mg, 0.37 mmol) at room temperature for 3 h. Analytical GC (FFAP) showed the formation of **8b**[35] (55%). The enal **8b** was isolated by preparative GC: oil; IR ($CHCl_3$) 2710, 1720, 1640, 905 cm^{-1}; ^1H NMR (400 MHz) δ 1.45 (2 H, m), 1.66 (2 H, m), 2.08 (2 H, m), 2.44 (2 H, dt, J = 2, 7 Hz), 4.99 (2 H, m), 5.79 (1 H, ddt, J = 17, 10, 6 Hz), 9.77 (1 H, t, J = 2 Hz); MS m/z 112 (M^+), 111, 94, 79 (base peak), 68, 55; HRMS calcd for $C_7H_{12}O$ (M^+) 112.0887, found 112.0879.

Grob Fragmentation of 9 with Iodosylbenzene and Boron Trifluoride (run 12 in Table I). To a suspension of **9** (35 mg, 0.066 mmol) and ISB (17 mg, 0.079 mmol) in 0.5 mL of dichloromethane was added a solution of BF_3–Et_2O (11 mg, 0.079 mmol) in 0.2 mL of dichloromethane at 0 °C. After being stirred at 0 °C for 30 min, the reaction mixture was quenched with brine and extracted with diethyl ether. The organic layer was dried over sodium sulfate and concentrated under aspirator vacuum. The crude product was purified by preparative TLC (8:2 hexane/ethyl acetate) to afford **11** (14.4 mg, 92%) as a mixture of regioisomers: IR (film) 3320, 1460, 1050, 955 cm^{-1}; ^1H NMR (100 MHz) δ 0.9 (3 H), 1.08–2.2 (24 H), 2.3–2.7 (1 H), 3.52–3.84 (1 H), 5.04–5.32 (1 H); MS m/z 238 (M^+), 220, 149, 121, 94, 55 (base peak); HRMS calcd for $C_{16}H_{30}O$ (M^+) 238.2296, found 238.2296.

Grob Fragmentation of 9 under MOPMO Conditions (run 13 in Table I). According to the general procedure, **9** (32 mg, 0.06 mmol) was treated with ISB (16 mg, 0.07 mmol), BF_3–Et_2O (10 mg, 0.07 mmol), and DCC (15 mg, 0.07 mmol) at room temperature for 3 h. The crude product was purified by preparative TLC (8:2 hexane/ethyl acetate) to give the enal **10** (2.5 mg, 18%) and **11** (10 mg, 71%). **10**: IR ($CHCl_3$) 2700, 1720, 1640, 1460, 890 cm^{-1}; ^1H NMR (400 MHz) δ 0.88 (3 H, t, J = 7 Hz), 1.2–1.6 (16 H), 1.78 (2 H, quint, J = 7 Hz), 1.99 (2 H), 2.05 (2 H), 2.43 (2 H, dt, J = 1.5, 7 Hz), 4.71 (1 H), 4.75 (1 H), 9.78 (1 H, t, J = 1.5 Hz); MS m/z 238 (M^+), 220, 149, 135, 121, 94, 79, 41 (base peak); HRMS calcd for $C_{16}H_{30}O$ (M^+) 238.2297, found 238.2327.

Grob Fragmentation of 12 under MOPMO Conditions (run 14 in Table I). According to the general procedure, an 89:11 cis/trans mixture of **12** (28 mg, 0.16 mmol) was treated with ISB (42 mg, 0.19 mmol), BF_3–Et_2O (27 mg, 0.19 mmol), and DCC (40 mg, 0.19 mmol) at room temperature for 3 h. Analytical GC showed the formation of **8a** (18%). Preparative TLC (8:2 hexane/ethyl acetate) gave **12** (62%).

Preparation of *trans*-2-Decyl-3-(tributylstannyl)cyclohexanone (14). To a solution of (tributylstannyl)lithium (0.33 M THF solution, 27 mL, 8.94 mmol) was added dropwise 2-cyclohexen-1-one (859 mg, 8.94 mmol) at –50 °C, and the mixture was stirred for 15 min at the temperature. 1-Iododecane (2.29 mL, 10.7 mmol) was added dropwise to the mixture over 10 min,

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and the mixture was allowed to warm to room temperature. After 22 h at room temperature, additional 1-iododecane (1.0 mL, 4.67 mmol) was added, and the mixture was stirred for 20 h. The reaction mixture was quenched by the addition of an aqueous NH_4Cl solution and extracted with diethyl ether. Usual workup left an oil, which was purified by flash chromatography (18:1 hexane/ethyl acetate) to give the *trans*-ketone **14** (2.24 g, 47%): IR (film) 1705, 1460, 1375, 1070, 655 cm^{-1}; ^1H NMR (400 MHz) δ 0.83–0.92 (9 H), 0.90 (9 H, t, J = 7 Hz), 1.13–1.78 (34 H), 1.97 (1 H, m), 2.12 (1 H, m), 2.37 (2 H, m); ^{13}C NMR (25 MHz) δ 213.8 ($J(^{119}Sn-^{13}C)$ = 44.2 Hz), 54.9 ($J(^{119}Sn-^{13}C)$ = 14.9 Hz), 42.8, 34.4, 32.4, 32.0, 31.9, 30.4, 30.1, 29.7, 29.4, 28.2, 27.6 ($J(^{119}Sn-^{13}C)$ = 54.2 Hz), 22.8, 14.1, 13.6, 9.4 ($J(^{119}Sn-^{13}C)$ = 306 Hz); MS m/z 471 (M^+ – Bu, base peak), 291, 235, 179; HRMS calcd for $C_{24}H_{47}OSn$ (M^+ – Bu) 471.2649, found 471.2649.

Isomerization of 14 to *cis*-2-Decyl-3-(tributylstannyl)-cyclohexanone (15). To a solution of **14** (280 mg, 0.53 mmol) in 15 mL of dioxane–methanol (1:2) was added 5 mL of an aqueous 0.5 N NaOH solution, and the mixture was heated at reflux for 43 h. The reaction mixture was neutralized with 1 N hydrochloric acid at 0 °C and extracted with diethyl ether. The organic layer was washed with brine, dried over sodium sulfate, and concentrated. The crude product was purified by flash chromatography (18:1 hexane/ethyl acetate) to afford an inseparable mixture of **14** and **15** (269 mg, 96%). The ratio of **14**:**15** was determined to be 62:38 by the ^{13}C NMR spectrum: ^{13}C NMR (25 MHz) δ 214.2 ($J(^{119}Sn-^{13}C)$ = 33.7 Hz, **15**), 213.7 ($J(^{119}Sn-^{13}C)$ = 44.2 Hz, **14**), 55.2 (**15**), 54.9 (**14**), 42.8 (**14**), 40.1 (**15**), 34.4 (**14**), 33.5 (**15**), 32.4, 32.0, 31.2, 30.4, 30.1, 29.7, 29.3, 28.2, 27.8, 27.6, 22.7, 14.1, 13.6, 9.5, 9.4.

Reduction of 14 with Lithium Aluminum Hydride. To a solution of **14** (935 mg, 1.77 mmol) in 15 mL of THF was added $LiAlH_4$ (135 mg, 3.54 mmol) at 0 °C, and the mixture was heated at reflux for 1 h. Flash chromatography (10:1 hexane/ethyl acetate) gave 481 mg of **16** (51%) and 271 mg of **17** (29%). **16**: IR (film) 3310, 1460, 1375, 1075, 1025, 660 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H, m), 0.88 (3 H, t, J = 7 Hz), 0.90 (9 H, t, J = 7.1 Hz), 1.20–1.60 (36 H), 1.78 (2 H, m), 1.97 (1 H, m), 3.36 (1 H, dt, J = 4, 10 Hz, $W_{1/2}$ = 22.5 Hz); ^{13}C NMR (100 MHz) δ 73.9 ($J(^{119}Sn-^{13}C)$ = 63.5 Hz), 48.0 ($J(^{119}Sn-^{13}C)$ = 14.0 Hz), 36.2, 33.2 ($J(^{119}Sn-^{13}C)$ = 16.5 Hz), 31.9, 31.5 ($J(^{119}Sn-^{13}C)$ = 15.3 Hz), 30.7, 30.0, 29.7, 29.7, 29.4 ($J(^{119}Sn-^{13}C)$ = 19.5 Hz), 29.4, 29.0, 27.9, 27.7 ($J(^{119}Sn-^{13}C)$ = 56.1 Hz), 24.8, 22.7, 14.1, 13.7, 8.9 ($J(^{119}Sn-^{13}C)$ = 302 Hz); MS m/z 473 (M^+ – Bu), 359, 291, 251 (base peak), 177, 132; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ – Bu) 473.2805, found 473.2829. **17**: IR (film) 3370, 1460, 1375, 960, 660 cm^{-1}; ^1H NMR (400 MHz) δ 0.81 (6 H, m), 0.88 (3 H, t, J = 7 Hz), 0.89 (9 H, t, J = 7 Hz), 1.20–1.60 (37 H), 1.83 (2 H, m), 3.93 (1 H, m, $W_{1/2}$ = 9 Hz); ^{13}C NMR (100 MHz) δ 67.5 ($J(^{119}Sn-^{13}C)$ = 43.3 Hz), 44.6 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 33.3, 31.9, 30.7, 30.0, 29.7, 29.7, 29.4 ($J(^{119}Sn-^{13}C)$ = 19.5 Hz), 29.4, 27.6 ($J(^{119}Sn-^{13}C)$ = 53.7 Hz), 27.0, 26.5 ($J(^{119}Sn-^{13}C)$ = 345 Hz), 22.7, 22.3 ($J(^{119}Sn-^{13}C)$ = 53.7 Hz), 14.1, 13.7 ($J(^{119}Sn-^{13}C)$ = 20.1 Hz), 9.1 ($J(^{119}Sn-^{13}C)$ = 301 Hz); MS m/z 473 (M^+ – Bu), 471 (base peak), 291, 235, 179, 132; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ – Bu) 473.2805, found 473.2826.

Reduction of the Mixture of 14 and 15 with Lithium Aluminum Hydride. A 62:38 mixture of **14** and **15** (240 mg, 0.455 mmol) was reduced with $LiAlH_4$ (35 mg, 0.91 mmol). Flash chromatography (12:1 hexane/ethyl acetate) and preparative TLC (9:1 hexane/ethyl acetate) afforded 100 mg of **16** (41%), 49 mg of **17** (20%), and 84 mg of **18** (35%). **18**: IR (film) 3400, 1460, 1375, 1040, 960, 660 cm^{-1}; ^1H NMR (400 MHz) δ 0.82 (6 H), 0.88 (3 H, t, J = 7 Hz), 0.89 (9 H, t, J = 7 Hz), 1.10–1.70 (38 H), 1.80 (1 H, m), 3.78 (1 H, dt, J = 6.8, 3.9 Hz, $W_{1/2}$ = 14.5 Hz); ^{13}C NMR (100 MHz) δ 72.6 ($J(^{119}Sn-^{13}C)$ = 41 Hz), 45.4 ($J(^{119}Sn-^{13}C)$ = 13.5 Hz), 32.1, 31.9, 31.2 ($J(^{119}Sn-^{13}C)$ = 44 Hz), 30.4, 29.7, 29.7, 29.6, 29.5, 29.4, 29.4, 29.3, 28.0, 27.7, 24.4, 22.7, 14.1, 13.7, 10.0 ($J(^{119}Sn-^{13}C)$ = 301 Hz); MS m/z 473 (M^+ – Bu), 251 (base peak), 177, 137; HRMS calcd for $C_{24}H_{49}OSn$ (M^+ – Bu) 473.2805, found 473.2776.

Grob Fragmentation of 16 under MOPMO Conditions. According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, **16** (101 mg, 0.19 mmol) was treated with ISB (50 mg, 0.23 mmol), BF_3–Et_2O (32 mg, 0.23 mmol), and DCC (47 mg, 0.23 mmol) at room temperature for 2 h. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give the *trans*-enal **19** (35 mg, 77%): IR (film) 2700, 1730, 1460, 1380, 965 cm^{-1}; ^1H NMR (400 MHz) δ 0.88 (3 H, t, J = 6.8 Hz), 1.26 (16 H), 1.70 (2 H, quint, J = 7 Hz), 1.97 (2 H, q, J = 7 Hz), 2.03 (2 H, q, J = 7 Hz), 2.42 (2 H, dt, J = 2, 7 Hz), 5.35 (1 H, dt, J = 15, 7 Hz), 5.42 (1 H, dt, J = 15, 7 Hz), 9.77 (1 H, t, J = 2 Hz); MS m/z 238 (M^+), 220, 194, 166, 98 (base peak), 82, 54; HRMS calcd for $C_{16}H_{30}O$ (M^+) 238.2296, found 238.2308.

Grob Fragmentation of 17 under MOPMO Conditions. According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, **17** (103 mg, 0.20 mmol) was treated with ISB (51 mg, 0.23 mmol), BF_3–Et_2O (33 mg, 0.23 mmol), and DCC (48 mg, 0.23 mmol) at room temperature for 2 h. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give the enal **19** (42 mg, 91%).

Grob Fragmentation of 18 under MOPMO Conditions. According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, **18** (45 mg, 0.09 mmol) was treated with ISB (22 mg, 0.10 mmol), BF_3–Et_2O (14 mg, 0.10 mmol), and DCC (21 mg, 0.10 mmol) at room temperature for 1.5 h. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give the *cis*-enal **20** (9 mg, 45%): IR ($CHCl_3$) 2700, 1720, 1600, 1460 cm^{-1}; ^1H NMR (400 MHz) δ 0.88 (3 H, t, J = 7 Hz), 1.26 (16 H), 1.70 (2 H, quint, J = 7 Hz), 2.00 (2 H, q, J = 7 Hz), 2.08 (2 H, q, J = 7 Hz), 2.43 (2 H, dt, J = 2, 7 Hz), 5.31 (1 H, dtt, J = 11, 7, 1.5 Hz), 5.42 (1 H, dtt, J = 11, 7, 1.5 Hz), 9.77 (1 H, t, J = 2 Hz); MS m/z 238 (M^+), 220, 194, 98 (base peak), 68; HRMS calcd for $C_{16}H_{30}O$ (M^+) 238.2296, found 238.2312.

Oxidation of 19 with Sodium Chlorite. Oxidation of **19** was carried out according to the procedure developed by Pinnick.[36] To a solution of **19** (34 mg, 0.16 mmol) and 2-methyl-2-butene (0.81 mL, 7.6 mmol) in 3.3 mL of *t*-BuOH was added dropwise a solution of sodium chlorite (134 mg, 1.48 mmol) and sodium dihydrogen phosphate (173 mg, 1.11 mmol) in 1.5 mL of water. After the reaction mixture was stirred at room temperature overnight, volatile components were removed under aspirator vacuum. The mixture was acidified to pH 2 with aqueous 10% hydrochloric acid and extracted with chloroform. The organic layer was washed with brine, dried over sodium sulfate, and concentrated to give an oil. The crude product was purified by preparative TLC (6:4:0.1 hexane/ethyl acetate/acetic acid) to give 31 mg (84%) of the acid **21**: IR (film) 1705, 1460, 1235, 965 cm^{-1}; ^1H NMR (400 MHz) δ 0.88 (3 H, t, J = 7 Hz), 1.26 (16 H), 1.70 (2 H, quint, J = 7 Hz), 1.97 (2 H, q, J = 7 Hz), 2.04 (2 H, q, J = 7 Hz), 2.35 (2 H, t, J = 7 Hz), 5.35 (1 H, dt, J = 15, 7 Hz), 5.44 (1 H, dt, J = 15, 7 Hz), 11.1 (1 H); MS m/z 254 (M^+), 236, 194, 152, 123, 97, 83, 69, 55 (base peak); HRMS calcd for $C_{16}H_{30}O_2$ (M^+) 254.2245, found 254.2238. The structure of **21** was determined by comparison with an authentic sample prepared by the reported procedure.[37]

Synthesis of *erythro*-6-Acetoxy-5-hexadecanolide (24). To a soltuion of **21** (19 mg, 0.074 mmol) in 0.22 mL of cyclohexane and 0.07 mL of toluene was added *m*-CPBA (89% purity, 22 mg, 0.10 mmol), and the reaction mixture was stirred at room temperature for 6 h. The resulting precipitate was filtered off and washed with 1 mL of cyclohexane. The combined filtrate containing the epoxide **22** was heated to reflux for 24 h. After the filtrate was cooled to room temperature, water was added, and the mixture was extracted with diethyl ether. The organic layer was washed with brine, dried over sodium sulfate, and concentrated under aspirator vacuum. The crude lactone **23** was dissolved in 1 mL of pyridine. Acetic anhydride (0.1 mL) was added, and the mixture was stirred for 48 h at room temperature. Aqueous 1 N hydrochloric acid was added, and the mixture was extracted with diethyl ether. The organic layer was washed with brine, dried over sodium sulfate, and concentrated. The crude product was purified by preparative TLC (7:3 hexane/ethyl acetate) to afford 9.3 mg (40%) of stereochemically pure **24**.[38] The structure and stereochemical purity of **24** were determined by

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comparison of the 400-MHz ^1H NMR spectrum with that of an authentic sample.

Preparation of *trans*-2-Ethyl-3-(tributylstannyl)cyclohexanone (25). To a solution of (tributylstannyl)lithium (0.33 M THF solution, 27.5 mL, 8.99 mmol) was added dropwise 2-cyclohexen-1-one (864 mg, 8.99 mmol) at -78 °C, and the reaction mixture was stirred for 20 min at -78 °C. A solution of iodoethane (0.86 mL, 11 mmol) and hexamethylphosphoric triamide (HMPA, 0.2 mL) in 2 mL of THF was added dropwise at -50 °C over 10 min, and the mixture was allowed to warm to room temperature. After 22 h at room temperature, additional iodoethane (0.43 mL, 5.4 mmol) was added, and the mixture was stirred for 18 h. The reaction mixture was quenched by the addition of an aqueous NH_4Cl solution and extracted with diethyl ether. Usual workup left an oil, which was purified by flash chromatography (18:1 hexane/ethyl acetate) to give the trans ketone **25** (2.58 g, 69%): IR (film) 1710, 1460, 1380, 1070 cm^{-1}; ^1H NMR (400 MHz) δ 0.79-0.93 (18 H), 1.22-1.82 (18 H), 1.97 (1 H, m), 2.12 (1 H, m), 2.36 (2 H, m); ^{13}C NMR (25 MHz) δ 213.9 ($J(^{119}Sn-^{13}C)$ = 44.0 Hz), 56.2 ($J(^{119}Sn-^{13}C)$ = 14.7 Hz), 42.9, 33.9 ($J(^{119}Sn-^{13}C)$ = 322 Hz), 32.4 ($J(^{119}Sn-^{13}C)$ = 61.5 Hz), 30.4 ($J(^{119}Sn-^{13}C)$ = 13.2 Hz), 29.3 ($J(^{119}Sn-^{13}C)$ = 20.5 Hz), 27.6 ($J(^{119}Sn-^{13}C)$ = 54.2 Hz), 24.6 ($J(^{119}Sn-^{13}C)$ = 19.1 Hz), 13.7, 12.6, 9.2 ($J(^{119}Sn-^{13}C)$ = 307 Hz); MS *m/z* 359 (M^+ - Bu, base peak), 291, 235, 179; HRMS calcd for $C_{16}H_{31}OSn$ (M^+ - Bu) 359.1397, found 359.1397.

Preparation of 2-Ethyl-1-methyl-3-(tributylstannyl)-cyclohexanol (26). The ketone **25** (830 mg, 2.0 mmol) was treated with methyllithium (0.6 M diethyl ether solution, 6.55 mL, 4.0 mmol) as in the preparation of **5a** to give an oil. The crude product was purified by flash chromatography (11:1 hexane/ethyl acetate) to give the alcohol **26** (537 mg, 62%) as an 89:11 mixture of stereoisomers and **25** (218 mg). **26**: IR (film) 3470, 1460, 1380, 1170, 925, 735 cm^{-1}; ^1H NMR (400 MHz) δ 0.84 (6 H), 0.90 (9 H, t, J = 7 Hz), 0.97 (2.67 H, t, J = 7 Hz), 1.02 (0.33 H, t, J = 7 Hz), 1.16 (0.33 H, s), 1.21 (2.67 H, s), 1.20-1.64 (22 H), 1.86 (1 H, m); MS *m/z* 375 (M^+ - Bu), 357, 291, 251, 235, 179, 123 (base peak), 95, 81; HRMS calcd for $C_{17}H_{35}OSn$ (M^+ - Bu) 375.1709, found 375.1681.

Grob Fragmentation of 26 under MOPMO Conditions. According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, **26** (105 mg, 0.24 mmol) was treated with ISB (64 mg, 0.29 mmol), BF_3-Et_2O (42 mg, 0.29 mmol), and DCC (60 mg, 0.29 mmol) at room temperature for 3.5 h. The crude product was purified by preparative TLC (9:1 hexane/ethyl acetate) to give the known *trans*-enone **27**[24,39] (23 mg, 67%): ^1H NMR (400 MHz) δ 0.96 (3 H, t, J = 7 Hz), 1.64 (2 H, quint, J = 7 Hz), 1.99 (4 H), 2.13 (3 H, s), 2.41 (2 H, t, J = 7 Hz), 5.36 (1 H, dtt, J = 15, 7, 1.5 Hz), 5.46 (1 H, dtt, J = 15, 7, 1.5 Hz).

Reaction of *cis*-Benzyl Ether 36 with the MOPMO Combination. According to the general procedure for Grob fragmentation of **5** under MOPMO conditions, *cis*-benzyl ether **36**[15] (41 mg, 0.09 mmol), prepared from *cis*-**7a**, was treated with ISB (23 mg, 0.10 mmol), BF_3-Et_2O (15 mg, 0.10 mmol), and DCC (21 mg, 0.10 mmol) at room temperature for 18 h. The reaction mixture was quenched with an aqueous NH_4Cl solution and extracted with dichloromethane. Usual workup left an oil, which was purified by flash chromatography (19:1 chloroform/methanol) to give the known chlorostannane **37**[15] (36 mg, 91%).

Reaction of 37 with Butylmagnesium Chloride. A solution of butylmagnesium chloride (1.3 M THF solution, 0.05 mL, 0.07 mmol) was added to a solution of **37** (9.2 mg, 0.02 mmol) in THF (0.5 mL) at room temperature, and the mixture was stirred for 5.5 h. The reaction mixture was quenched with an aqueous NH_4Cl solution and extracted with diethyl ether. Usual workup left an oil, which was purified by preparative TLC (19:1 hexane/ethyl acetate) to give the tributylstannane **36** (8.9 mg, 93%).

Acknowledgment. We thank Professor K. Mori of University of Tokyo for the spectral data of *erythro*-6-acetoxy-5-hexadecanolide.

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Activation of Reducing Agents. Sodium Hydride Containing Complex Reducing Agents. 31. NiCRAL's as Very Efficient Agents in Promoting Homo-Coupling of Aryl Halides

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Received March 2, 1989

Homo-coupling of aryl bromides and chlorides is efficiently performed with nickel-containing complex reducing agents NiCRA-bpy. In a number of cases the presence of alkali iodides improves the procedure. Yields are very high and a number of functional groups are resistant. The mechanistic and catalytic aspects of these reactions are discussed.

Introduction

The classical Ullmann reaction employs a copper-promoted coupling of aryl halides. This very useful reaction, however, presents a number of drawbacks:[1] (i) need of rather high reaction temperatures, (ii) yields often moderate, (iii) aryl chlorides, with a few exceptions, are unreactive, (iv) high sensitivity to steric hindrance, and (v) cross-coupling not easily performed.

The introduction by Semmelhack and co-workers[2] of zerovalent nickel complexes in place of copper brought a revival of interest on the old Ullmann reaction. One of the limitations of Semmelhack's condensations was the use of air-sensitive reagents generally prepared by cumbersome

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